Manual of Forensic Taphonomy

SECOND EDITION

EDITED BY

James T. Pokines
Ericka N. L'Abbé
Steven A. Symes

CRC Press
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Dr. Mark LeVaughn, friend and mentor

Steven A. Symes

My parents, Martha and Theodore

Ericka N. L'Abbé

Robert Marvin Pettyjohn, Lincoln-Washington Battalion,
KIA-BNR, Spanish Civil War, 1938

James T. Pokines

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Editor Biographies

James T. Pokines, Ph.D., D.-.A.B.F.A., is an Associate Professor in the Forensic Anthropology Program, Department of Anatomy and Neurobiology, Boston University School of Medicine. He is also the Forensic Anthropologist for the Office of the Chief Medical Examiner, Boston, Commonwealth of Massachusetts, and analyzes all unknown bone cases in that state. His prior experience includes 12 years as a Forensic Anthropologist and Manager at the Central Identification Laboratory, Hawaii, recovering and analyzing the remains of missing servicemembers from past conflicts. His field experience includes excavations in 18 countries, including modern forensic scenes in multiple countries, Tiwanaku sites in Bolivia, a Classical site in Egypt, modern scavenger dens in Kenya, and Paleolithic sites in Spain, France, and Jordan. He has ongoing research in the latter country, including the natural faunal trap site Wadi Zarqa Ma'in 1 and multiple Paleolithic sites in the Azraq basin. His taphonomic interests include scavenger gnawing and dispersal, subaerial weathering, and other environmental effects to bone, and he also researches zooarchaeology, paleoecology, and Paleolithic archaeology. He received his B.A. degree in Anthropology and Archaeology at Cornell University and his M.A. and Ph.D. degrees in Anthropology from the University of Chicago and is a former Vice President of the American Board of Forensic Anthropology and a current Fellow of the American Academy of Forensic Sciences.

Ericka Noelle L'Abbé, Ph.D., D.-A.B.F.A., is a Professor of Biological Anthropology and the Director of the Forensic Anthropology Research Centre (FARC) in the Department of Anatomy at the University of Pretoria, South Africa. She is Board-certified with the American Board of Forensic Anthropology and is a Fellow of the American Academy of Forensic Sciences. She teaches undergraduate and postgraduate students in biological anthropology, human osteology, human evolution and research methodology. She has published numerous papers and book chapters in forensic anthropology, with more recent focuses on facial approximations, teaching human evolution, and the development of medical implants for South Africans. As the Director of the FARC, she is involved in a variety of activities including the analysis of human remains, both forensic and archaeological in nature, field and laboratory training, research, and repatriation. She also applies knowledge and research in biological anthropology for application in medicine and health sciences education. She has written 350 technical reports on unknown skeletal remains for forensic pathologists and the South African Police Service (SAPS). She currently manages an Erasmus+ Capacity Building Grant in Higher Education that aims to build the first digital repository of skeletal remains in Africa, known as Bakeng se Afrika project, for the purposes of research and education.

Steven A. Symes, Ph.D., D.-A.B.F.A., is currently the Forensic Anthropologist for the Office of the Chief Medical Examiner in Jackson, Mississippi. He is Professor Emeritus of Forensic Anthropology at Mercyhurst University in Pennsylvania and an Adjunct Professor in the Department of Anatomy at the University of Pretoria, South Africa. He is a Diplomate of the American Board of Forensic Anthropology and a Fellow of the American Academy of Forensic Sciences. He is best known for his expertise in interpreting trauma to bone and is a leading authority on saw and knife mark analysis. With over 30 years of experience, he has assisted federal, state, local, and non-US authorities in the identification, analysis, and documentation of those suspected to be victims of trauma. Dr. Symes has been qualified as an expert for both the prosecution and defense, testifying specifically on forensic tool mark and fracture pattern interpretation in bone, as well as blunt force, ballistic, burned and healing trauma in bone. Because of his specialty in criminal dismemberment and mutilation, he has worked a number of serial homicides, and has provided analysis of cut marks in nearly 200 dismemberment cases and approximately 400 knife wound cases.

Contributor Biographies

Lucinda Backwell, Ph.D., is a researcher in the Instituto Superior de Estudios Sociales, CCT-NOA Sur (CONICET), Tucumán, Argentina, and an honorary researcher in the Evolutionary Studies Institute and DSI/NRF Centre of Excellence in Palaeosciences at the University of the Witwatersrand, Johannesburg, South Africa. As a former senior researcher at the University of the Witwatersrand, she was granted a doctoral degree in 2004 by this institution and the University of Bordeaux, France. She specializes in the evolution of bone tool technology in Africa, and identifying the agents responsible for bone modification in the fossil record. Her research interests include early hominin cultural and behavioral evolution, tracing the emergence of modern human behavior, the evolution of South American mortuary practices, and the ethno-archaeology of Kalahari San people.

Joan E. Baker, Ph.D., D.-A.B.F.A., has nearly 30 years of forensic laboratory and field experience in academics, federal government, the private sector, and cultural resource management, including field investigations and/or excavations in Vietnam, Laos, Cambodia, South Korea, Fiji, Jamaica, France, Belgium, Luxembourg, Italy, Germany, Slovenia, Croatia, Poland, Austria, the Netherlands, England, Texas, and New York. She also has worked on mass graves excavation and forensic analysis of remains in Iraq. Dr. Baker has three degrees in anthropology (B.A., M.A., and Ph.D.) from the University of Nebraska-Lincoln, Syracuse University, and Texas A&M University, respectively. She currently serves as a functional analyst and technical writer for the Scientific Research Corporation, and her work experience includes serving as a forensic anthropologist at the Defense POW/MIA Accounting Agency, scientific advisor and policy officer at the Defense Prisoner of War/Missing Personnel Office, and forensic anthropologist and laboratory manager at the Joint POW/MIA Accounting Command. Dr. Baker is a Diplomate of the American Board of Forensic Anthropology and a Registered Professional Archaeologist.

Stephanie Edwards Baker, M.Sc., is a researcher at the Palaeo-Research Institute, University of Johannesburg. Since 2011 she has been the co-director and primary permit holder of the Drimolen Fossil Hominin Site in the Cradle of Humankind, South Africa. Her early research focused on large raptor taphonomy in the Pleistocene of southern Africa, but has since expanded to include large carnivores and early hominin studies. Ms. Baker received her B.Sc. degree in zoology and conservation in 2011, her B.Sc. honors degree in geosciences in 2012, and her M.Sc. degree in palaeontology in 2014, all from the University of the Witwatersrand.

Eric J. Bartelink, Ph.D., D.-A.B.F.A., is a Professor in the Department of Anthropology and co-Director of the Human Identification Laboratory at California State University, Chico. He received his B.S. degree in Anthropology at Central Michigan University (1995), his M.A. degree in Anthropology at California State University, Chico (2001), and his Ph.D.

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Derek Congram, Ph.D., D.-A.L.A.F., is a board-certified forensic anthropologist and archaeologist. He has worked in more than 20 countries on archaeological, humanitarian and medico-legal projects for NGOs, governments, the United Nations, the International Criminal Court, and the International Committee of the Red Cross, among others. His research interests include geospatial analysis of clandestine burial sites and professional ethics. He promotes victim families as being central in forensic and humanitarian investigations.

Mary Davis, M.Sc., is a biological anthropologist who engages in interdisciplinary research in forensics, skeletal anatomy, physiology, and spectroscopic techniques. Davis earned a B.S. degree in neuroscience from Baylor University, a B.S. degree in anthropology from the College of Charleston, and an M.Sc. in forensic anthropology from the University of Central Lancashire in the UK. She was a Death Investigation Specialist for the Georgia Bureau of Investigation, where she assisted with autopsies and responded to death scenes. In 2017, Davis joined the Forensic Anthropology Center at the University of Tennessee, Knoxville, where she is currently the Assistant Director. She furthers her research into factors that affect the process of decomposition and postmortem interval estimation.

Heather Deel, B.S., earned her Bachelor's degree in Biology in 2017 at Sam Houston State University, where she investigated the core decomposer microbiome of humans at the Southeast Texas Applied Forensic Science Facility. She is currently a Ph.D. candidate in the cell and molecular biology program at Colorado State University, where she researches microbial succession of decomposing bone as a potential tool for estimating the long-term postmortem interval. In addition to research, she has written a book chapter on using microbiome tools for estimating the postmortem interval for *Microbial Forensics*, co-authored a review on using animal models for understanding the microbial decomposition of human remains, and she is in the process of publishing multiple other works in this field.

Francesco d'Errico, Ph.D., is the Director of Research of exceptional class with the Centre National de la Recherche Scientifique, University of Bordeaux, and Professor at the Centre for Early Sapiens Behaviour, University of Bergen. His academic interests focus on the evolution of human cognition and the emergence of symbolic cultural practices in Africa and Eurasia, the evolution of bone technologies, Neanderthal extinction, and the impact of climate change on cultural evolution. He has published hundreds of articles in high impact academic journals and is the author or editor of several research monographs. Included since 2014 by Clarivate Analytics in the list of the world's most cited researchers, he has just been awarded with three other colleagues a large ERC Synergy Grant to investigate the origin of numerical cognition.

Tosha L. Dupras, Ph.D., is a Professor of Anthropology, and currently serves as the Interim Dean of the College of Sciences at the University of Central Florida (UCF). Dr. Dupras received her B.A. degree in Archaeology from Simon Fraser University, an M.Sc. degree in Human Biology and Human Kinetics from the University of Guelph, and her Ph.D. degree in Anthropology from McMaster University. Her research interests include forensic archaeology, bioarchaeology, stable isotope and dietary analysis, human growth and development, and paleopathology. Dr. Dupras' field research includes sites in Egypt, Sudan, France, Lithuania, and S.E. Asia. Dr. Dupras has authored/coauthored numerous journal articles and book chapters, and is a coauthor of *Forensic Recovery of Human Remains: Archaeological Approaches.*

Alexandra L. Emmons, Ph.D., is a classically trained anthropologist with a focus in biological anthropology. She earned a B.A. in anthropology and a B.S. in biology from the University of Georgia. In 2012, she pursued an M.A. in anthropology from the University of Tennessee, Knoxville (UTK), where she examined the persistence of human DNA in the soil throughout cadaveric decomposition at the Anthropology Research Facility, UTK. In 2015, she continued decomposition and molecular research at UTK in pursuit of a Ph.D. in anthropology. Her doctoral research focused on human skeletal DNA preservation and the postmortem skeletal microbiome associated with individuals from different depositional environments. She is currently continuing research on the postmortem skeletal microbiome as a postdoctoral researcher at Colorado State University.

Tom Evans, Ph.D., attended the University of Washington and earned B.S. degrees in geological sciences; biochemistry; cell and molecular biology; and ecology, evolution and conservation biology. He then attended Washington University and earned an M.A. degree in Paleobiology. He spent two years teaching and tutoring in the Seattle area before returning to graduate school to earn a Ph.D. in Earth Sciences and a Certificate in College Teaching at Montana State University. His research focused on fluvial taphonomy, specifically the transport and deposition of bones and articulated body parts in rivers.

Arthur Gill Green, Ph.D., holds the position of College Professor of Environmental Geography and Geographical Techniques at Okanagan College and serves as a Research Associate at the University of Guelph. His research focuses on environmental governance and the application of Geographic Information Science to human rights issues. Since 2005, he has worked as a consultant in several complex political emergencies, led workshops for human rights organizations on how to gather evidence of war crimes and crimes against humanity, and co-led investigations on the spatial aspects of killer behavior in locations such as Bosnia-Herzegovina, Nagorno-Karabakh, and Myanmar.

James du Guesclin Harrison, Ph.D., is the Zoological Curator of the Wits Life Sciences Museum (WLSM) which is part of the School of Animal, Plant & Environmental Sciences at the University of the Witwatersrand, Johannesburg, South Africa. James was awarded a doctoral degree in entomology at the University of Pretoria, South Africa in 2014. James' research focusses on African scarab beetle taxonomy and biology, insect pollination (especially in the Kruger National Park), and invertebrate modification of bone.

Nicholas D. Higgs, Ph.D., is the Director of the Cape Eleuthera Institute in the Bahamas, the research and innovation branch of The Cape Eleuthera Island School. His doctoral research focused on the taphonomy of marine mammals in deep-sea environments, particularly the ecology and palaeo-ecology of *Osedax* bone-devouring worms. This research has now broadened out to investigating organic matter cycling in tropical marine environments, with a focus on chemosynthetic energy pathways in marine food webs.

Jennifer Lai Hipp, B.S., is an M.S. degree candidate in human biology at the University of Indianapolis. Her research focus is on molecular taphonomy and the ability to generate DNA profiles from burned bone. She currently serves as an assistant in the University of Indianapolis Forensic DNA Laboratory. Jennifer received a Bachelor of Science in Forensic Sciences from Chaminade University of Honolulu and a Certificate in Applied Forensic Anthropology from University of Hawai'i-West O'ahu.

Jean-Bernard Huchet, Ph.D., is an entomologist at the CNRS (French National Centre of Scientific Research), working at both the National Museum of Natural History, Paris, and the University of Bordeaux, France. In 1996, he initiated a new discipline, dubbed "Funerary archaeoentomology", which aims to interpret past funerary practices from the study of insect remains recovered from archaeological contexts. At the same time, he is specialized in the field of taphonomy and more particularly in the study of osteolytic alterations perpetrated by insects on human and faunal bones. In this respect, he has written several book chapters and papers that are references on this topic.

Miranda M. E. Jans, Ph.D., started at the Defense POW/MIA Accounting Agency (DPAA) with an ORISE fellowship to study the preservation of bone microstructure and DNA in relation to pre-burial treatment of remains. Currently, she continues to work for DPAA as a Contract Lead and Anthropologist for SNA International. Dr. Jans has an M.Sc. degree in medical biology from the University of Amsterdam. Her doctoral and post-doctoral research at VU University, Amsterdam, contributed to the understanding of bone preservation in relation to various burial environments. She collaborated on several research projects during her time with ORISE, investigating the use of bone histology in micromorphological analysis, as well as continuing research on the preservation of archaeological and forensic bone.

Natalie Keough, Ph.D., is currently an Assistant Professor and Course Director in the Department of Anatomy and Cellular Biology at Khalifa University in the newly established College of Medicine and Health Sciences. She completed her undergraduate B.Sc. degree in Human Physiology in 2004 at the University of Pretoria (UP), South Africa and completed her postgraduate studies and obtained a Ph.D. (Anatomy) in 2014 at UP. Her Ph.D. research focused on establishing a novel method for estimating the varying stages of decay from thermally altered remains. Her work was able to show several thermal alteration characteristics on bone that are distinctly associated with different stages of decomposition. Currently, she is busy establishing a research niche in the United Arab Emirates (UAE) with a focus on forensic anthropological methods of identification (ancestry, sex, age) applied to local population groups using available imaging modalities (x-ray, CT, and MRI). Concurrently, she is continuing her musculoskeletal research, which focuses on establishing safe surgical zones for various orthopaedic procedures in collaboration with both surgeons in the UAE and South Africa.

Marcelle LaCroix, M.S., is currently a detective with the Camden County Prosecutor's Office in New Jersey and is assigned to the Crime Scene Investigations Unit, which responds to and assists with criminal investigations and death investigations within Camden County. Since joining the Camden County Prosecutor's Office in 2015, she graduated from the New Jersey Police Training Commission Basic Course for Investigators in 2016 and has received training in crime scene photography, latent fingerprint classification and comparison, shooting reconstruction, and forensic archaeology. Prior to joining the Camden County Prosecutor's Office, she worked as a Crime Scene Analyst for the Camden County Metro Police Department Crime Scene Unit for approximately two years. She obtained her M.S. degree in Forensic Anthropology from the Boston University School of Medicine in 2013 after receiving her B.A. degree in Anthropology from Stockton University in 2011.

Krista E. Latham, Ph.D., D.-A.B.F.A., is a Professor of biology and anthropology at the University of Indianapolis. She is a board-certified forensic anthropologist and the Director of the University of Indianapolis Human Identification Center. Her research investigates different aspects of skeletal biology, population genetics and transfer DNA. She currently serves as a Consulting Forensic Anthropologist for police, coroners, and pathologists in the Midwestern US and also serves as a DNA Expert in the US Court System.

Leandi Liebenberg, M.S., is a lecturer in the Department of Anatomy at the University of Pretoria (South Africa). As part of her duties at the Forensic Anthropology Research Centre (FARC) she has worked on over 100 forensic cases and assists in training postgraduate students in skeletal analyses. She currently teaches courses in forensic anthropology, biological anthropology, bone pathology, and research methodology.

Maritza Liebenberg, M.S., is a Research Assistant in the Department of Anatomy at the University of Pretoria. In 2020, she completed her Masters of Science dissertation pertaining to thermal alteration in a South African veldt fire context. Her research focused on the combined effect of bone condition and fire duration on ten standard anthropological measurements of the femur. When Maritza is not working as a Research Assistant, she spends her time peer-reviewing current forensic cases for the Forensic Anthropology Research Centre and lecturing undergraduate and honors students in human osteology.

R. Lee Lyman, Ph.D., is Professor Emeritus of Anthropology at the University of Missouri, Columbia. A scholar of late Quaternary paleozoology, human prehistory of the Pacific Northwest United States, and the history of North American archaeology, he is author of *Vertebrate Taphonomy* (1994), *Quantitative Paleozoology* (2008), and *Theodore E. White and the Development of Zooarchaeology in North America* (2016), and co-author of *Paleozoology and Paleoenvironments: Fundamentals, Assumptions, Techniques* (2019).

Megan E. Madonna, M.S., received her M.S. degree in Human Biology from the University of Indianapolis where her research and publications focused on skeletal DNA, transfer DNA, and molecular taphonomy. While at the University of Indianapolis she served as an assistant in the Molecular Anthropology Laboratory working on skeletal DNA analyses. She is currently a Senior Crime Scene Analyst with the Las Vegas Metropolitan Police Department and an adjunct at the College of Southern Nevada teaching Investigative Photography.

Diana L. Messer, Ph.D., is a forensic anthropologist and an Assistant Professor of Anthropology at Western Carolina University. She received her M.S. in forensic and biological anthropology from Mercyhurst University and her Ph.D. in anatomy from The Ohio State University. Dr. Messer has worked on or assisted with forensic cases at various institutions. She worked for two years as a forensic anthropologist in support of the Defense POW/MIA Accounting Agency in Hawai'i, was a Visiting Scientist at the New York City Medical Examiner's Office, and she also worked as a postdoctoral faculty member at Mercyhurst University. Dr. Messer's primary research examines fracture healing in children in cases of suspected physical abuse.

Jessica L. Metcalf, Ph.D., is a microbiome scientist who leads highly interdisciplinary, innovative research projects that span the fields of forensics, animal science, and health by combining experimental ecology, large genomic datasets, and bioinformatics tools. She earned a B.S. degree in chemistry from University of Georgia and a Ph.D. in ecology and evolution from University of Colorado Boulder. She completed postdoctoral positions in ancient DNA at the University of Adelaide in South Australia and in microbiome science at UC San Diego. She joined Colorado State University (CSU) in 2016 as part of the Microbiome Systems Cluster Hire Initiative. She is an Associate Professor in the Department of Animal Sciences at CSU, where her laboratory studies the complex suite of microorganisms (bacteria, archaea, fungi, protists, etc.) driving decomposition of postmortem vertebrate animals. Over the past several years, she has been developing a microbial clock to estimate how long vertebrate (including human) remains have been decomposing.

Briana Pobiner, Ph.D., is a paleoanthropologist whose zooarchaeological and taphonomic research centers on meat-eating in the evolution of Stone Age human diets with a focus on the use of bone surface modifications including human butchery marks and predator tooth marks on modern and fossil bones. She has conducted fieldwork, experimental studies, and collections-based research in Indonesia, Kenya, Romania, South Africa, Tanzania, and the US. She joined the Smithsonian in 2005 as a research fellow to help curate the Hall of Human Origins, and now leads the Human Origins Program's education and outreach efforts while continuing her research. She is also an Associate Research Professor of Anthropology in the Center for the Advanced Study of Human Paleobiology at the George Washington University. She holds a B.A. degree in Evolutionary Studies from Bryn Mawr College and M.A. and Ph.D. degrees in Anthropology from Rutgers University.

Corey Pollock, M.S., completed her B.S. degree in anthropology at The Ohio State University and received an M.S. degree in Forensic Anthropology from the Boston University School of Medicine. While completing her M.S. research, she was involved in additional forensic research projects resulting in multiple publications in scientific journals. She is currently working within the field of forensics as a Crime Scene Investigator.

Carrington S. Schneider, M.S., is an alumna of the Forensic Anthropology Program at Boston University School of Medicine. Her research focused on alligator taphonomy, completing her titled thesis *Alligator Taphonomy: An Analysis on Gnawed and Digested Bone*. She is currently employed as a contractor for the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) as a Crime Gun Intelligence Analyst.

John J. Schultz, Ph.D., is a Professor and Chair of the Department of Anthropology at the University of Central Florida (UCF), and he has a secondary joint appointment at the National Center for Forensic Science (NCFS) at UCF. Dr. Schultz received his M.S. degree in Human Biology from the University of Indianapolis, and his Ph.D. in Anthropology from the University of Florida. His research interests include forensic and archaeological applications of ground penetrating radar (GPR) for grave detection, timing of injury, taphonomy, medicolegal forensic significance of skeletal remains, and scene reconstruction and documentation of scenes involving skeletal remains. Dr. Schultz has authored/coauthored a number of journal and book chapter publications, and he is a coauthor of *Forensic Recovery of Human Remains: Archaeological Approaches*. Additionally, he is a Fellow of the Anthropology Section of the American Academy of Forensic Sciences, and he is a practicing forensic anthropologist for the local medical examiner's office.

Pearl Perouz Seferian has a significant family history involving witnessing genocide. Before he escaped from a Bolshevik prison and came to Canada in 1922, Pearl Perouz Seferian's father, Misak Seferian, wrote his eyewitness account of the events that he witnessed or participated in during the Armenian Genocide of 1915. Pearl edited and published his diary accounts in the book *Resistance: A Diary of the Armenian Genocide 1915–1922*. Her father daily documented the hunger, thirst, and brutality during the forced caravan march over dangerous mountain terrain. The thirty-two women and children of their family all died. Misak has given the location of thousands of bodies that he has seen and often noted how they were killed. Pearl has witnessed the long-term effects of genocide on survivors and knows firsthand that the impact of their trauma is passed on to subsequent generations.

Christine A. Spiegel, M.S., C.C.S.I., is a Forensic Scientist for the Arapahoe County Sheriff's Office at the Unified Metropolitan Forensic Crime Laboratory in Englewood, Colorado. She previously worked for the Asheville Police Department in western North Carolina as a Forensic Services Technician and for the Massachusetts Attorney General's Office in Boston, MA as an Investigator. She has taught college level courses in crime scene investigation and forensic laboratory practices. She received her B.A. degree in anthropology and criminal justice from Colorado State University and her M.S. degree in forensic anthropology from the Boston University School of Medicine.

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Josephine M. Yucha, M.S., is a Principal Investigator and Osteologist at Cultural Surveys Hawai'i, Inc. She has been conducting archaeological studies and burial investigations throughout the State of Hawai'i since 2010. Ms. Yucha received her B.A. degree in anthropology from the University of Pittsburgh in Pittsburgh, PA, her M.S. in forensic and biological anthropology from Mercyhurst University in Erie, PA, conducted a three-year research fellowship at the former Joint POW/MIA Accounting Command – Central Identification Laboratory on Hickam AFB, HI, and continued studies at the University of Hawai'i at Mānoa in Honolulu, HI. Her research topics have included positive/victim identification from radiographic analyses, taphonomy, ancestral dental traits, and Hawaiian prehistory.

Taylor Yuzwa, M.S., earned her M.S. degree in forensic and biological anthropology from Mercyhurst University in 2013.

Introduction
The Importance and Use of Forensic Taphonomic Data

1

JAMES T. POKINES

Contents

> Here is a fruit for the crows to pluck
> For the rain to gather, for the wind to suck
> For the sun to rot, for the trees to drop
> Here is a strange and bitter crop
>
> **—Abel Meeropol**
> *Strange Fruit*

Goals of the Second Edition

The main goals in any forensic skeletal analysis are to aid in answering who is the person represented (individualization), how did that person die (trauma/pathology), and when did that person die (the postmortem interval or PMI). The analyses conducted to address these goals include the determination of human, nonhuman, or nonosseous origin, the minimum number of individuals represented in an assemblage, age at

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death, sex, stature, ancestry, perimortem trauma, antemortem trauma, osseous pathology, odontology, radiology of selected portions, and taphonomy. These analyses are also performed in conjunction with the field processing of the recovery scene and the interpretation of the site formation and postdepositional history. These analyses together are used to form the biological profiles of the individual(s) present, which in turn narrow the identification of those remains or in some cases lead to their positive identification. The patterns of perimortem and antemortem trauma may aid other medicolegal specialists in the determination of the cause and manner of death. All of these other analyses become incrementally more difficult or impossible with increased bone fragmentation, general surface degradation, dispersal, and loss of skeletal elements. Whether these bones were made unavailable for analysis through their actual destruction or through their nonrecovery due to dispersal by water, gravity, carnivores, or the lack of a suitable archaeological field system, the overall effect is the same regarding the information lost. These analytical problems parallel those of other disciplines, including the field of biological anthropology as a whole, zooarchaeology, and vertebrate paleontology, where taphonomic changes often lead to information loss.

The taphonomic condition of a set of remains therefore is a standard aspect of forensic anthropological analysis and report generated for a case (ABFA 2021). These data are not collected just to describe the current condition of a set of remains: they inform multiple aspects of the entire understanding of a case. These include the environment(s) in which the remains were deposited (buried, terrestrial surface, marine, freshwater, or some artificial setting). Taphonomic effects (i.e., the actual modifications to an individual bone or assemblage; Lyman [1994]) from nonhuman biological or environmental agencies also should be analyzed to avoid confusing them with modifications (i.e., trauma) caused by human agencies during homicide, dismemberment, transport, or concealment. While taphonomic processes can be highly destructive and subtract information from bones regarding their utility in determining other aspects of the biological profile, they also add information (Behrensmeyer and Kidwell 1985; Binford 1981) regarding the entire postmortem history of the remains and the relative timing of these effects (Ubelaker 1997; Chapter 20). Taphonomic observations also constitute the majority of data available to estimate the PMI.

Taphonomic processes affecting skeletal remains leave behind alterations, macroscopic (Lyman 1994; Micozzi 1991) and microscopic (Nielsen-Marsh and Hedges 2000; Chapter 2), which can be "read" and interpreted. Indeed, the patterning of present versus missing skeletal elements can be interpreted as well (Chapter 4). The aim of the present volume is to categorize these alterations to skeletal remains, illustrate and explain their significance, and demonstrate how to diagnose differentially among them where possible (Pokines 2018a, 2020). These observations may then be combined into higher-order patterns to aid forensic investigators in determining what happened to those remains in the interval from death to analysis. It is rare that a single type of alteration has affected a set of skeletal remains, and the overlapping markers of multiple types of skeletal alteration are typically left upon them, often from more than one depositional environment (Chapters 8 and 20). Since these processes affect other vertebrates in similar manners, this volume will be of use to other disciplines, and relevant information derived from these other disciplines is also presented here.

While the present volume is primarily focused upon large vertebrate and specifically human skeletal remains, it synthesizes data from human (Berryman et al. 1991, 1997;

Nawrocki 1995; Rogers 2005; Schultz et al. 2003), ethological (Patterson 1996; Peterson 1977; Pobiner 2007; Pobiner et al. 2020), geological/paleontological (Behrensmeyer 1991; Martin 1999; Voorhies 1969), paleoanthropological (Brain 1980, 1981; Hill 1980; Shipman 1981), archaeological artifactual (Odell and Cowan 1987), and zooarchaeological (Binford 1981; Binford and Bertram 1977; Fisher 1995; Lyman 1994, 2008; Payne 1983) studies. Apart from the similarities in postmortem changes between humans and other large vertebrates (Micozzi 1991; Pokines 2016), studies utilizing nonhuman fauna have the benefit of typically much larger sample sizes (Behrensmeyer 1991) to add to forensic taphonomic discussions as well as the greater availability for experimental analyses. Indeed, pigs (*Sus scrofa*) are the most common analog used for humans in forensic experiments of all kinds, given their overlapping characteristics with humans (bone density, range of adult body mass, subcutaneous fat stores, skin thickness, hair covering, and omnivorous diets) and the ubiquity of purpose-bred pigs for experimentation in university settings (Bonney and Goodman 2021; DeBruyn et al. 2021; Matuszewski et al. 2020). Nonhuman remains can be left exposed outdoors to natural forces with fewer strictures on their placement or (often justifiable) concern of the public, and often for longer durations. Human remains from decomposition studies also are usually expected to yield at the end of soft-tissue decomposition a largely intact human skeleton for subsequent research and teaching, so most highly destructive taphonomic processes affecting osseous remains directly (e.g., large vertebrate scavenging and dispersal, extensive subaerial weathering, acidic soil corrosion, thermal alteration, abrasion, cracking from drying, etc.) are actively avoided (Synstelien 2015). It is also important to note that zooarchaeological samples typically can be orders of magnitude larger than human samples from the same broad depositional setting (with some exceptions mostly coming from cemetery settings) or modern observational studies of humans.

While this volume covers differentiation between perimortem trauma and postmortem damage (Chapter 13), broad treatment of human-induced perimortem trauma (gunshot wound, blunt force trauma, etc.) is too large and varied a topic to cover effectively here. It is logical to group this type of trauma under the broader category of taphonomy, if one views human-induced damage to bone as another specialized type of taphonomic alteration. Like other types of taphonomic alteration, human-induced trauma may begin at the time of death or continue into the PMI through dismemberment and burial (Chapter 5) of remains. Human transportation of remains in both wartime and homicide settings is covered in Chapter 10, and human ritual, anatomical teaching, and trophy-collecting taphonomic characteristics are covered in Chapter 8. The effects of archaeological recovery upon remains recovered are discussed in Chapter 17.

Taphonomy

The study of these changes in biological remains from the time of death until their recovery and analysis is referred to as *taphonomy*. The term taphonomy was coined by Efremov (1940:93) in his famous article, defining it as the science of "the laws of embedding", i.e., burial. This first interest in taphonomic changes in organisms emerged among geologists and paleontologists, curious about why and how the fossils that they found were preserved, and how observations of processes ongoing today would explain what had gone on in the past. Though preceded by other early geologists, James Hutton in his *The Theory of the*

Earth (1788) first published the principle of *uniformitarianism*: the Earth's sedimentary rocks were accumulated by the same processes of sediment deposition visible in contemporary rivers and seas. This concept is applied throughout taphonomic investigations, where observations of bone-altering processes today are applied to the past. While taphonomy as a named discipline dates only from Efremov's (1940) work, earlier investigations into that specific topic exist. As early as 1823, Buckland (1823:93) had noted that "the bones of various birds, of moles, water-rats, mice" had been accumulated in limestone caves by the "agency of hawks", while fish bones had been accumulated in the same sites by gulls. This relationship between the type of osseous remains recovered and the species that had fed upon them, dispersed them, or in some cases reconcentrated them (Chapter 9) was to become central in twentieth- and twenty-first-century investigations of taphonomy. The early geologist Charles Lyell (1830–1833:II:219–227) discussed how animal remains could accumulate in the deposits of caves and fissures by their acting as natural pit traps over long periods. In this manner, he noted that these remains often became associated with those of humans.

In terms of direct alteration of bones themselves, Wedl (1864) examined postmortem microscopic changes to bone and found taphonomic changes in the form of microtunneling (*Wedl tunnels*) damage (Chapter 2). Examining more specifically the decomposition and potential long-term preservation of vertebrate remains, Johannes Weigelt, a German professor of geology and paleontology, published *Rezente Wirbeltierleichen und ihre paläobiologische Bedeutung* (Recent Vertebrate Carcasses and Their Paleobiological Implications) in 1927, where he examined naturally occurring death assemblages such as the mass kills of large ungulates and their subsequent bone deposition (Weigelt 1989 [1927]). The direct link between observations of contemporary natural processes and their use in interpretation of events of the past is the core of this research, just as is common in more recent studies in forensic taphonomy including observations of animal behavior and natural physical forces such as marine transport affecting human remains (Haglund and Sorg 1997, 2002). Paleontologists, however, also have the unique problem of attempting to understand the ecological relationships of species with no modern analogs, an aspect explored in Shotwell's (1955) seminal paper that presented a method for interpreting the paleoecological abundance of taxa within an assemblage and the biases affecting bone preservation. More actualistic experimental approaches to taphonomy emerged in the ensuing decades, including the early work of Voorhies (1969) in the use of water flume experiments to study the transport potential of large vertebrate remains to interpret remains from paleontological sites. By the 1970s taphonomic research integrated into the analysis of biological remains became the norm (Behrensmeyer 1978; Behrensmeyer and Kidwell 1985; Binford and Bertram 1977; Miller 1969, 1975).

While a full discussion of all aspects of vertebrate taphonomy is not the focus of the present volume, some common terms are presented here. Those looking for more extensive references are referred to excellent works by Allison and Briggs (1991), Donovan (1994), Fernández-Jalvo and Andrews (2016), Lyman (1994, 2008), and Martin (1999). The following interrelated definitions follow Lyman (1994:503–513) and references therein. A taphonomic *effect* is the actual alteration to a bone, such as staining, leaching of mineral content, bleaching, tooth marking, or abraded area. A taphonomic *agent/agency* is the general class of what caused the effect. Categories of agent include groupings like carnivores, birds, scavengers in general, humans, ultraviolet radiation, or saltwater. A taphonomic *process* is how the bone became modified, such as trampling, sediment agitation, or digestion. A taphonomic effect such as a tooth puncture, for example, could be caused by a canid (the agency), and the process would be gnawing, specifically with a tooth crown piercing the cortical bone (Chapter 9).

Forensic Taphonomy

Forensic taphonomy is more a descriptive term than a practical boundary, given the profuse overlap in taphonomic analytical techniques, data collected, interpretations, and goals with those of other anthropological and paleontological fields. A forensic anthropologist estimates the age of a recent human skeleton in much the same manner that a biological anthropologist estimates the age of a human skeleton from an excavation of an ancient (pre-Inka) Tiwanaku site in the Andes, citing many of the same standard sources, such as Buikstra and Ubelaker (1994) for basic biological profile data and Wedel and Galloway (2014) for perimortem trauma. As stated previously, there are also wide areas of overlap with vertebrate zooarchaeology and paleontology (Behrensmeyer 1991), where, for example, much of the early data regarding weathering (Behrensmeyer 1978) are still cited (Buikstra and Ubelaker 1994) in biological/forensic anthropology works, including the present volume (Chapter 11).

Forensic taphonomy (still) is also the least-quantified analytical subfield of forensic anthropology, perhaps due in part to this overlap with and reliance upon other disciplines, but also due to a lack of basic research in some areas, especially regarding human (or other species acting as proxy) skeletal degradation across a range of environments over prolonged periods. Also lacking is a comprehensive comparison of common taphonomic observations, the sets of environmental circumstances that caused them, and the places where confusion may occur when making observations and interpreting them. The present volume exists in part to help address these shortcomings. Forensic taphonomy also has some problems relatively unique to itself and the parameters under which it operates.

Time Frames Involved

Forensic anthropology concerns itself with a generally briefer time frame than other disciplines of biological anthropology or archaeology, and much shorter time frames than geology and paleontology (Pokines 2009; 2018a). Many crime scenes or potential crime scenes are on the order of hours to days old before they are reported to and investigated by law enforcement. The PMI may increase to years in the case of remains such as those discovered in sealed homes, where the decedent's death went unnoticed or unreported. The interval also is increased for remains hidden in more rural locations that prevented their discovery (Haglund 1997a) or massive crime scenes such as the World Trade Center that yielded previously undiscovered osseous remains years later simply because it took so long to process the scene to recover them (Sledzik et al. 2009). Mass burials investigated for evidence of war crimes are typically on the order of years or decades old (Chapter 10). This delay is typical, since the conflict that produced them often takes years or more to be resolved and allow outside aid agencies into an area (where their data collection may produce evidence indicting members of current or recent governments). Deeper into the PMI, historical burials are (by definition) decades or centuries old (Chapter 5). These often must be investigated as if they are of forensic interest until determined otherwise, and the disturbance or looting of historical graves may be of law enforcement interest. Sites of archaeological or paleontological interest are usually not mistaken for those of forensic interest, but sometimes must be treated as pertaining to the latter category until proven otherwise (e.g., the famous cases of the Kennewick Man in the United States [Owsley and Jantz 2015] or the Bronze Age Ice Man in the Italian Alps [Ruff et al. 2006]).

All of these temporal categories share the early PMI, where decomposition, consumption, and most dispersal occur. Study of this subdiscipline of taphonomy is sometimes termed *necrology* (Behrensmeyer and Kidwell 1985), where the initial changes following death and the loss of soft tissue are examined. A bone encountered during these earlier stages, with more associated soft tissue attached externally or contained internally, is of higher resource potential to other species coexisting in the depositional environment. Most destructive processes affecting skeletal remains occur during the early phases after death, when the bone is attached to or contains more nutrients: if the bone can survive beyond the initial mortality incident and the numerous changes that may occur in the next few years, and be deposited in a location favorable to long-term preservation, then its chances for survival into the historical, archaeological, and paleontological periods with potential for later discovery become much greater. The taphonomic subdiscipline of *biostratinomy* examines the processes prior to and leading up to burial, including transport, dispersal, and sedimentation, which is followed temporally by *diagenesis*, the chemical changes occurring to a bone after burial (Behrensmeyer and Kidwell 1985). The vast majority of bones, of course, do not survive to reach the processes examined in studies of biostratinomy or diagenesis, or the surface of the Earth would be covered in bone. While it is difficult to survey the surface or excavate in most terrestrial environments and not locate some kind of bone from the local vertebrate fauna, that same bone likely would not survive in a recognizable state decades or centuries later. Exceptions occur in some artificial environments, including some cemeteries or grander burial environments such as extensive Old World urban catacombs or Egyptian monuments. They also occur in some natural environments, such as where burial in undisturbed sediments occurred quickly (L'Abbé et al. 2015) or especially in limestone caves where their neutral-to-low alkaline pH sediments and overall protective environment greatly increase bones' chances for surviving into the paleontological time range (Brain 1981; Pokines et al. 2011).

Osseous analysts studying these older PMIs are as curious about the very early PMI (relative to those remains, i.e., the events immediately following the death of a species millions of years ago) as are forensic anthropologists investigating contemporary human decomposition. All bones must survive this phase (necrological) to reach the later phases (biostratinomic and diagenetic), and the early phase often determines if the bone survives at all and if the bone makes it into a depositional setting where it can be preserved for later discovery. In terms of vertebrate taphonomy, these disciplines have much in common. One must also note that in many settings, other large vertebrates besides humans (including other hominins) pass through the same or very similar phases of taphonomic alteration, so the examination of zooarchaeological specimens is highly relevant to forensic taphonomy. Cross-pollination between these disciplines therefore is very productive, both in terms of past research and future joint research (L'Abbé et al. 2015).

Analytical Process

The analytical process (Pokines 2018a) used to assess forensic cases proceeds through multiple stages (Figure 1.1) that are broken into three broad questions: (1) what is it (i.e., is it even osseous), (2) how old is it, and (3) from what context does it come?

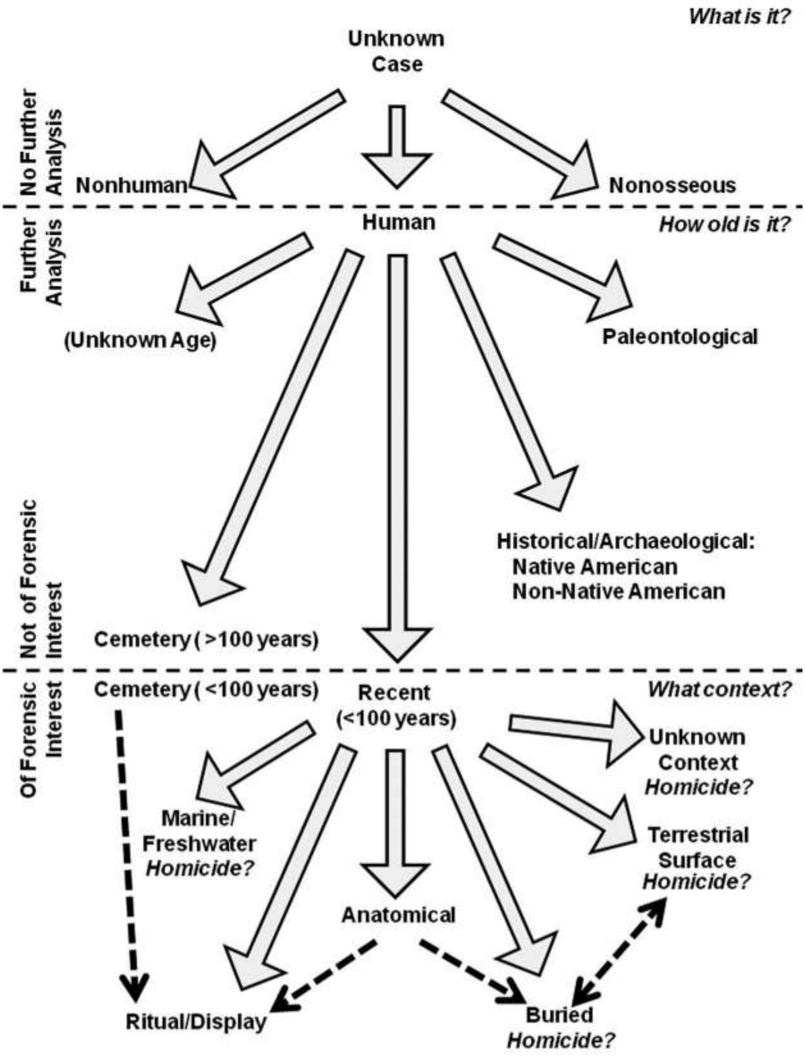

Figure 1.1 Stages of forensic taphonomic analysis, proceeding through what are the remains, how old are they, and what is their context(s) (Pokines 2018a; used with permission, *Journal of Forensic Identification*.)

Nonosseous, Nonhuman, and Human

Analysis begins in any case with the differentiation among nonosseous, nonhuman, and human remains. The first two categories do not require in most cases any further analysis. Nonosseous remains can originate along with cremains (Chapter 14, Figure 14.1) and be mistaken in the field for the latter. Stone, plant material (especially burnt), and shell (Christensen et al. 2012) are sometimes mistaken for bone. Nonosseous remains also can take the form of replicas of human remains (plastic or ceramic) that look realistic in photographs or from a distance and were initially mistaken for genuine human bone. Nonhuman remains can be a large proportion of the overall forensic anthropological caseload (Pokines 2020), yet they are unlikely to take up more than a small fraction of overall time expenditure. Nonhuman remains, however, are a very useful source of taphonomic data within a given jurisdiction and supply useful specimens for teaching (Pokines 2015).

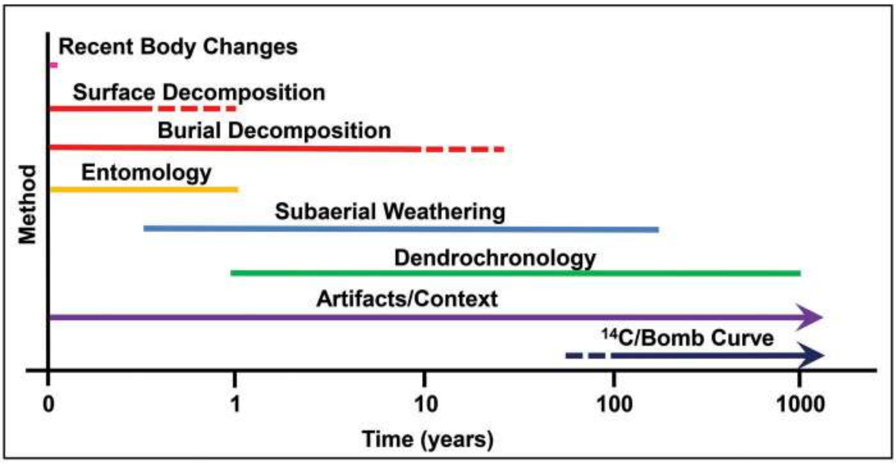

Figure 1.2 Methods used for absolute dating and the times scales that they span. The time scale is logarithmic. (Modified after Junod 2013:3.)

Time since Deposition

Many types of cases can be eliminated from further forensic consideration based upon a determination that they are of too old a PMI (Figure 1.2). This analytical phase can be thought of as determining the *temporal jurisdiction* of remains, as their age determines which government agency is ultimately responsible for them. Where the age is unknown and could be recent/modern, a forensic anthropologist is normally involved to aid in this determination. It should be noted that in the broadest sense, any case that is brought in for analysis is of "forensic interest" (or at least forensic anthropological interest), though it may not be of further law enforcement interest (Pokines 2020). The forensic anthropologist may have to spend just as much time on and write a comparable report for remains that turn out to be of cemetery or historical origin, and the taphonomic analysis provides much of the justification for that determination. Time since deposition has some correlation with location of deposition, since some environments are unlikely to preserve remains long term. These include terrestrial surface environments, where the destructive processes of and dispersal by scavengers (Chapters 9, 16, 18, and 19), subaerial weathering (Chapter 11), and slow coverage by the buildup of plant detritus make finding and processing sites much more difficult over time. Buried remains are more likely to survive long term, but they present their own obstacles to detection. Special contexts, including remains in ice, give longer-term protection to remains, but these sites are rare (Pilloud et al. 2016; pers. obs.). There is also some overlap during this stage with the previous stage, as nonhuman remains also can have an archaeological origin. Unless the older nonhuman remains are of interest to the state archaeological office or other agency, their antiquity also excludes them from further forensic interest.

Laws in the US vary by state regarding the temporal limit for remains, just by their time since death, to be no longer of forensic interest and under the control of the state archaeological agency. This PMI is sometimes up to 150 years (Pokines et al. 2017; Ubelaker and Grant 1989), and in the author's home jurisdiction (Massachusetts), this is set at 100 years. In rare cases actual fossil (palaeontological) remains are mistaken for something more recent, likely through unilateral turnover to law enforcement by someone unclear on their origin. The taphonomic characteristics and the context of the remains are used to estimate the PMI (Duhig 2003; Chapter 5), the latter of which may include associated artifacts or an advanced degree of soil horizon development above the burial. In particular, former cemetery remains commonly come under forensic anthropological analysis (Pokines et al. 2016; Chapter 5) and are subject to a temporal limit.

Other methods can be used to supply absolute dating (Figure 1.2), including radiocarbon dating, where taphonomy and context are insufficient. Radiocarbon analysis can include use of the "bomb curve", the abrupt spike in atmospheric ^{14}C caused by frequent above-ground nuclear testing from 1950 to 1963 (Ubelaker 2014). Analysis of different osseous tissues (teeth and bones) with their different times of carbon incorporation can determine if the remains span the peak in atmospheric ^{14}C levels. The growth of annual ring structures (tree rings) in tree roots growing above or through skeletal remains can be used to determine a minimum absolute time of deposition (Pokines 2018b; Quatrehomme et al. 1997; Willey and Heilman 1987). Subaerial weathering allows estimation of absolute dating, but a high amount of variation is known to exist based upon environmental and other factors (Chapter 11). Greater refinement of PMI estimation using this method is needed, as it bridges a gap between methods that are used for older contexts and those that are used for more recent ones, including decomposition and entomology (Chapter 3) and immediate changes to a body after death, including rigor mortis, livor mortis, and algor mortis (Geberth 2006).

Taphonomic Context

For the human remains that have been determined to have a PMI less than the temporal limit for that jurisdiction (Figure 1.1), the taphonomic analytical emphasis shifts to understanding the context of the remains from the effects that environment caused (see below). Human remains, however, often pass through more than one taphonomic environment (Figure 1.1; see also Chapter 20). For example, cemetery remains are likely to come under forensic anthropological analysis precisely because they have been disturbed from their burial context and have ended up dispersed upon the terrestrial surface, thus taking on a new set of taphonomic effects; they also may be repurposed for display or ritual uses (Chapter 8). Other common contexts for recent remains include freshwater (Chapter 6) or marine (Chapter 7) environments or their preparation and use as teaching specimens or trophies (Chapter 8). In the case of recent remains, the question of whether they resulted from homicide is always considered, with some contexts indicating that the answer is likely negative.

Other Problems in Forensic Taphonomic Analysis

Forensic anthropologists do not always perform their own field recovery of skeletal remains. They are often given remains by others associated with law enforcement and asked to reconstruct what may have happened to these remains during the PMI and to estimate the PMI itself. In these cases, the forensic anthropologist essentially must read the taphonomic history from the remains (Chapter 20), with no other initial sources of information. This may occur in other cases because the information is neither known nor suspected. Whether voluntary or involuntary, this procedure is known as *blind analysis* and also applies to the other portions of the biological profile (age, sex, population affinity, etc.). In some cases, forensic anthropologists are expected to perform voluntarily a blind analysis and deliberately have been given no information on the taphonomic history of the remains or suspected identity/biological parameters; that is, the suspected identity of the individual and the general provenance of the remains are known, but these are not disclosed to the skeletal analyst until after the analysis. This procedure is standard in many forensic anthropology laboratories, especially where a larger analytical staff is present and multiple layers can be placed between the person who makes initial contact with the external agency or internal branch supplying the remains (Holland et al. 2008; Chapter 21).

Information Loss, Information Gain

One may come to believe that taphonomy is nothing but a series of statements of bad news (Stiner 1994). As indicated above, taphonomic processes reduce the portions of a biological profile that can be generated and in particular lead to a loss of individualizing characteristics of a skeleton. Especially susceptible to destructive processes are the physical characteristics of the pubic bones and the midfacial area, with all their potential information regarding age, population affinity, and sex. Epiphyses and metaphyses (especially unfused ones) are easily destroyed and with them their information regarding developmental age. Similarly, long bones and other elements useful for the determination of stature can no longer be measured after the relatively fragile epiphyses have been eroded. Sternal rib ends, with their potential aging information, stand very little chance of survival in many depositional settings. General surface erosion throughout the skeleton makes complete measurements impossible, again causing a loss of potential metrical information to estimate sex and ancestry. Teeth, while often the most durable part of the skeleton, are not immune to damage and loss: single-rooted teeth often fall out of the maxilla and mandible after the loss of soft tissue and are not recovered in the field, and anterior teeth are particularly prone to thermal destruction as a body burns. Tooth roots also erode and lose eruption stage data. Elements already damaged and scattered by perimortem trauma (gunshot wound, high-speed impact, etc.) are even more susceptible to further postmortem damage, especially the perimortem fracture surfaces with their distinctive characteristics (Ubelaker and Adams 1995). Taphonomic processes also degrade DNA and decrease the potential for positive identification using these methods (Chapter 15). It is easy to see taphonomic changes as wholly negative processes.

Taphonomic analysis is filled with other caveats. Bones do not have to pass through a singular taphonomic trajectory and in practical experience almost never do (Chapter 20). Consider a common forensic scenario where an individual is shot and the body is dumped in the woods. The initial lethal trauma may have damaged some of the bones. The remains next may be partially eaten and dispersed by canids and smaller scavengers or decomposers, with some elements consumed or dispersed for hundreds of meters and tooth marks left behind on the surviving remains (Carson et al. 2000; Haglund 1997a; Willey and Snyder 1989). Decomposition of soft tissues may proceed rapidly (Chapter 3) and deter scavenging carnivores until it subsides. The surviving skeletal remains may lie on the surface for several years and variably undergo subaerial weathering (Behrensmeyer 1978) on their exposed surfaces and acidic topsoil erosion and staining on their contact surfaces (Gordon and Buikstra 1981; Pokines 2016; White and Hannus 1983; Chapter 11). Once the bones are dry and weathered, rodents such as porcupines (*Erethizon dorsatum*), squirrels (Sciuridae), and rats (*Rattus* spp.) may gnaw on them and transport them from where they were deposited by previous scavengers (Haglund 1997b; Chapter 9). Gravity and water may disperse the remains downhill or downstream, with differential innate transportability affecting how far different elements are transported and dispersed (Voorhies 1969; Chapter 6). The slow buildup of decomposing leaf litter may partially bury some elements (Pokines 2009; Pokines et al. 2019), making them much more difficult to locate even when otherwise exposed on the surface. They may become commingled with unrelated remains, likely of nonhuman large vertebrate species dying in the vicinity. The original set of skeletal remains, if any are discovered after all of this destruction and movement, may display overlapping traces of some or all of these taphonomic processes. It is the task of the forensic anthropologist to sort out these conflicting signals and place them in correct temporal order to reconstruct the postmortem history backward from the recovered remains to their original living source. The collection and analysis of all of these data are akin to the diagnosis of perimortem skeletal trauma or pathological conditions in bone, where all changes in bone differing from their living, healthy states must be examined, and even then, a single diagnosis may not be possible.

Taphonomic processes also *add* information (Behrensmeyer and Kidwell 1985; Binford 1981). In the example given above, each process has left traces (i.e., effects) upon the bone. The perimortem fracturing or other damage caused during the homicide may still be visible. Scavengers, including large mammals and rodents, leave their tooth marks behind and disperse (and reconcentrate) bone in ways that are sometimes patterned, allowing these changes to be distinguished from human activity. Subaerial weathering of bone has been studied for decades (Behrensmeyer 1978; Miller 1975), and this gradual process of bleaching and cracking can be distinguished from broadly similar changes such as cremation/calcination as well as give some indication of the PMI. Loss of bone may be understood by comparisons with known survivability rates (i.e., a femur midshaft is far more likely to survive long term than a sternum, due to the greater density of the former's cortical bone; Chapter 4) and natural processes that delete bone. In many cases, bones record their postmortem history by the alterations caused to them, be these cut marks, surface cracking and bleaching, adhering fauna, mineralization, marks from plant roots, algae growth, adherent sediments, thermal alteration, overall patterns of recovery, the loss of cortical surface and epiphyses in patterned areas, or with retained tooth markings. These types of alterations are divided into three broad categories, based upon the information gained: contextual, temporal (absolute timing of events), and perimortem vs. postmortem (relative timing of events).

Contextual Information

Contextual taphonomic information concerns what forces have acted upon and altered those remains and what it indicates about the history of those remains between the time of death and the time of analysis (Chapter 20). These include both macroscopic and microscopic (Chapter 2) alterations to bone. These may indicate depositional context: in what environment(s) did skeletal remains spend the majority of their time, or at least enough time so that the environment could leave visible alterations on bone (or destroy or disperse bones to such a degree that they were not recovered at all)? Examples of depositional context include multiple types of burial (primary, secondary, coffin, etc.) and their multiple subtypes vs. surface deposition of remains. The actions of biological agencies, such as plants, fungi, and vertebrate and invertebrate scavengers, are also affected greatly by the context of the remains during the PMI and therefore may be indicators of that context. Context also may extend to different types of artificial alteration to bone (Chapter 8), such as reburial, storage, and alteration for cultural purposes (trophy-keeping, scientific study, etc.). Multiple types of contextual information also may apply, as in remains that have undergone multiple taphonomic processes in multiple environments due to their dispersal.

Transport is another major aspect of contextual information: how and to where bones got moved/dispersed after death, from their initial point of deposition to their recovered location, and if reconcentration in a different location occurred through a human or natural agency (water, scavengers, etc.). Water transport of whole decomposing bodies or of individual skeletal elements is a frequent cause of bone transport (Chapters 6 and 7), as is bone-carrying by large carnivores and other vertebrate taxa (Chapters 9, 16, and 19). Understanding differential movement of disarticulated skeletal elements by these forces is also crucial for understanding the context of what remains are recovered and what remains are missing from a scene. This must be contrasted with what elements were likely destroyed by different forces, as modified by the inherent survivability of different elements due to their structural properties (Chapter 4). A bone lost from a scene due to dispersal easily may be misinterpreted as a bone lost due to its actual destruction, so potential transport of skeletal elements must be an integral part of contextual taphonomic analysis.

The process of contextual taphonomic analysis also includes assembling data and interpreting those data that are relevant to the manner of death (i.e., homicide, suicide, accidental, natural, or undetermined) and the cause of death (the original underlying medical condition that initiates the lethal chain of events that culminated in death), although these final determinations are in the realm of medical examiners and coroners. Any type of damage or alteration to bone may be relevant to these determinations, if only to rule out some type of taphonomic alteration as having a mundane, postmortem natural cause instead of a perimortem, human-induced one (Chapter 13). The role of forensic taphonomy in these cases often lies in the elimination of multiple scenarios, especially where these indicate that nothing of legal interest occurred. These scenarios can include that an otherwise unidentified bone is likely nonhuman in origin due to its taphonomic state (fresh, butchered, cooked, etc.). Cases such as these often form the bulk of casework in a medical examiner's office (Pokines 2020), so their efficient processing allows more time to be devoted to cases of forensic interest.

Temporal

Some taphonomic changes aid in the estimation of the PMI (Figure 1.2), as we learn more about the timing of alterations to bone from multiple sources. These include subaerial weathering—exposure causing drying, bleaching, and eventual flaking (Behrensmeyer 1978; Chapter 11). This category also includes more general indicators of the PMI, such as the stages of decomposition during the early PMI (Chapter 3) and how they lead to skeletonization and disarticulation, plant growth through bones, or large carnivore consumption and scattering. All of this temporal information is used to estimate the amount of time that has elapsed between the death of the individual(s) in question and the recovery of remains. This is an important part of the identification process, since it may greatly help narrow the range of possible identities for a given set of remains, thus amounting to an indirect form of individualization.

Temporal information is also integral to the establishment of the order of taphonomic changes as they occur (or co-occur) on a set of remains (Chapter 20). Noting that perimortem sawn surfaces are weathered and stained and have adherent algae (all of which take, at a minimum, months to develop in most environments) to the same degree as the surrounding un-sawn bone surfaces confirms the likely perimortem origin of that sawing. Similarly, noting prior markers of burial on remains now disarticulated and scattered on the terrestrial surface indicates the chain of events as they occurred (burial first, then dispersal) and some of the possible agencies involved (inhumation by humans, followed by accidental exhumation by burrowing animals, active scavenging, or water erosion). The margins of the sawn surface of the remains in this example then may be gnawed upon by rodents (Chapter 9), which would be determined under analysis as having occurred later in the temporal chain of taphonomic events. Other taphonomic clues, however, may establish the temporal chain of these changes to bone, or these events may be estimated and placed in order based upon known behavior of other species or typical taphonomic paths in a given environment (Chapter 20). As indicated above, temporal information also may separate remains of forensic interest from those that are not.

Perimortem vs. Postmortem Alteration

Another important forensic taphonomic analytical category is the differentiation of human from natural alteration of bone (Fisher 1995; Miller 1969; Morlan 1984). Again, human alteration to bone (perimortem trauma) is of specific interest to forensic anthropologists, given that the reconstruction of the events surrounding death is one of the main reasons that their analytical skills are sought by law enforcement agencies. Acts of violence may leave traces upon bone, which may be obscured or destroyed by later, unrelated taphonomic processes, or other postmortem forces may cause damage to bone, which can be mistaken for perimortem trauma. More precisely, taphonomic analysis often focuses upon the differentiation between perimortem trauma from *pseudotrauma* (postmortem damage to a bone that superficially or more deeply appears to be perimortem in origin). Naturally, the presence of such postmortem alteration to bone, if misdiagnosed as perimortem trauma, can result in serious legal ramifications for that case. This type of analysis (Chapter 13) includes differentiation between sharp force trauma vs. postmortem marking on bone (incidental scratches, carnivore tooth marks, etc.); blunt force trauma vs. postmortem sources of bone breakage (animal gnawing, weakening through decomposition and postmortem erosion, etc.); and thermal alteration to fresh bone vs. dry, already skeletonized bone (Chapter 14). This type of analysis is also restricted by a relative dearth of studies involving exactly how long the perimortem (or, more accurately, "wet-bone") interval extends (Satish 2020; Ubelaker and Adams 1995; Wheatley 2008), especially regarding how long do bones have to age after death before they no longer fracture in the same manner as in a living or recently deceased individual (Chapters 13 and 14).

"Natural" alteration, however, may include details of death information of significance to law enforcement. Death by wild animal attack is an obvious example, and this predation upon a human may lead to both perimortem trauma from the initial fatal attack damaging bone and to subsequent postmortem alteration as feeding on the deceased person proceeds and remains are dispersed. Death from accidental falls from height or drowning also have a high natural component, in the sense that the primary agency of death was a part of the natural world (sudden impact into hard surfaces or water) and as such may have had the largest amount of influence over immediate (massive perimortem blunt force trauma) or later (water transport and feeding by marine species) taphonomic effects to those remains. As difficult as it may be to study and codify the full range of taphonomic variation caused in various natural environments, it is less difficult than to study and codify the full range of human behavior causing death of other human beings through all types of homicide, including psychosis-induced interpersonal violence, neglect, abuse, deliberate withholding of life-giving aid, war, terrorism, and genocide directed at civilian populations. The motivations for these types of acts may be difficult to comprehend, but the actions used to hide evidence of them may follow clear, rational patterns (Chapter 10).

One must note that some taphonomic changes can occur in an identical manner regardless of their ultimate origin being a criminal act of killing a person or subsequent efforts to dispose of the remains vs. these events having an accidental, suicidal, or unrelated natural origin. Bones caught in a brush fire, whether that fire was intentionally set to hide evidence of a crime or started by a random lightning strike or tossed cigarette, are going to burn in a manner broadly indiscernible from each other. Wolves finding a fresh body in a forest often feed on it in a manner that is later taphonomically indistinguishable from a person that the wolves have killed themselves. Falls from great height, such as from tall bridges, may result in the same trauma pattern if the individual fell accidentally or was pushed off. The intent of the organism in most cases (and certainly any natural force) is neutral in terms of the taphonomic effects that it causes, the major exception to this rule being human action (Chapters 10 and 13).

Taphonomic Suites of Characteristics

The practical aim of this volume is to present a system to organize the gathering of macroscopic and microscopic taphonomic observations common to forensic anthropology cases, to interpret and explain those observations and how they vary, and to recognize these alterations on bone and distinguish them from each other. Groups of these taphonomic characteristics sometimes may form a *taphonomic signature*, defined as a suite of observations, often combined with other lines of evidence, that can indicate a unique set of forces, taphonomic history event, or process that altered a set of skeletal remains. Unambiguous signatures, however, are rare in taphonomic analysis for multiple reasons. Some alterations to bone are too indistinct or their traces are too easily removed by subsequent taphonomic degradation to be detected by the time that the bone can be analyzed (Fernández-Jalvo and Andrews 2003, 2016). It will also be made clear that these suites of taphonomic effects are usually overlapping on the same set of skeletal remains; that is, it is rare that just a single type of taphonomic alteration from one wholly unambiguous cause is present on a bone. In addition, some suites of taphonomic alterations are obvious subsets of other related processes, and some suites of taphonomic alterations can themselves be combined into higher-order groupings in order to explain broader patterns of postmortem processes.

Some taphonomic suites of characteristics are very basic and require little elaboration. Without thinking much about it, archaeologists and biological anthropologists recognize the characteristics of a primary burial or secondary burial, and how they overlap with each other. A primary burial is usually characterized by articulation of skeletal elements, a largely complete skeleton, soil staining and/or adherence, plant root damage and invasion, erosion (in acidic soil) of cortical surfaces, and a lack of subaerial weathering. A secondary burial may have most of these characteristics, but with disarticulation of the skeletal elements, loss of smaller skeletal elements, and other markers of having been transported and reburied (postmortem breakage, ritual treatment, etc.) likely in a much smaller grave. Other suites of taphonomic characteristics are more complex, atypical, or specialized, can be ascribed to more than one possible cause, or frequently co-occur with other types of alteration. Examples are discussed in Chapters 8 and 20, where cases of repurposed human remains came from one context and ended up in a different context as display items.

Data Collection for Common Taphonomic Alterations to Bones

Chapter 21 presents checklists for the gathering of taphonomic data. These taphonomic alterations and the processes that cause them are covered in Chapters 2 through 19. Recovery contexts include common forensic scenarios or those potentially mistaken for forensic scenarios. These include multiple burial types (primary and secondary, coffin, and multiple subtypes based upon differences in substrate including bog, ice, and forest); human interventions including plowing, cremation, dismemberment, curation, anatomical preparation, ritual utilization, and trophy-collecting; the effects of multiple types of animal scavenging (large mammals, rodents, birds, reptiles, and arthropods); and other depositional contexts greatly impacting osseous remains (freshwater, saltwater, and surface exposure).

Other Lines of Evidence

Other lines of evidence beyond osseous remains viewed in isolation may be just as vital in the determination of their origin as the taphonomic effects that they accumulated prior to their examination in a laboratory. These always must be taken into consideration. For example, excavating a set of remains that appears to be of prehistoric origin might be reinterpreted if modern artifacts are found in association with those remains. Was it mixing of burial fill contaminated with later artifacts? Was the determination of prehistoric origin in error? Was a larger assemblage of modern artifacts not recovered due to a recent body being stripped prior to burial, in order to decrease the chances of later identification? The reverse situation (recent remains being mistaken for those of historic or prehistoric origin) can occur if older artifacts get mixed, unnoticed, with burial fill. Similarly, the clear recovery context of the remains may be known to the forensic anthropologist examining them, as that person may have done the excavating. In cases like these, each known recovery scene becomes a natural laboratory for taphonomic effects to human remains, and the forensic anthropologist is then in the position to gather additional data regarding that particular environment. Given that a large portion of what has been determined about taphonomic effects occurring to human remains has been achieved by the slow accumulation of data from individual forensic case studies (Haglund and Sorg 1997, 2002) combined with actualistic experimental results, this source of data should be collected whenever possible (Chapter 21).

Other forms of naturally caused alterations are also important in determining the taphonomic history of human remains. The signs that carnivores, rodents, and other scavengers (Chapters 9, 16, and 19) may leave at a scene include damage to soft tissue and artifacts, tracks in the ground, fur, and feces, all of which are important clues to the origins of taphonomic effects to a set of skeletal remains. Some species, especially smaller wild species, household pets, or domesticated farm animals, still may be present at a scene (Steadman and Worne 2007). Exclusion of some taphonomic forces, such as subaerial weathering from buried remains or wild carnivore scavenging from remains found in a sealed building, is also an obvious source of information to narrow down the possibilities encompassing the total postmortem history of a set of skeletal remains.

Future Forensic Taphonomic Research

In all forensic taphonomic analyses (and educational programs), one of the primary goals should be the separation of natural processes from artificial (i.e., human actions of legal relevance), so a clear understanding of natural processes and the inherent physical and chemical properties of bone is necessary. Indeed, a natural explanation for all potential forensic taphonomic effects should be the default until proven false. These natural processes and properties that must be considered first include the normal progression of decomposition (Chapter 3), the inherent differences in the durability of skeletal elements (Chapter 4), environmental degradation of bone through chemical and biological factors (Chapter 5), water transportation and damage (Chapter 6), chemical and biological processes in marine environments (Chapter 7), animal gnawing and dispersal (Chapters 9, 16, 18, and 19), environmental exposure and mineral diagenesis (Chapters 2, 11, and 12), thermal alteration (Chapter 14), and how these processes may affect bone on a microscopic (Chapter 2) and organic molecular (Chapter 15) level and the potential to derive aging and DNA data from bone. Similarly, taphonomic alterations left by human actions that have an origin unrelated to forensic matters must be eliminated from contention, including non-clandestine burial (Chapter 5), incidental marking on bone including from excavation damage (Chapter 17), and deliberate alteration of bones for anatomical teaching, ritual, or trophy-collection reasons (Chapter 8). Only then can interpretations of human actions of direct forensic interest be accepted with confidence, including such processes as the deliberate movement of remains (Chapter 10) and perimortem trauma (Chapter 13).

In concordance with this need for training in natural processes, taphonomy is amenable to actualistic, small-scale research projects and as such meshes well with the parameters of student research, both at the master's and doctorate levels (Lloveras et al. 2016). Given the ongoing expansion in the field of forensics and the number of programs with outdoor research facilities (Chapter 3), taphonomic projects of all kinds lend themselves well to student research in terms of need and practical budgetary limitations. Longer-term research also is needed. Many questions in forensic taphonomy relate to the PMI and how bone changes over the course of decades, especially subaerial weathering (Chapter 11). Experimental designs to determine the characteristics of bone recovered from a variety of microenvironments—including fleshed bodies at the base of mass burials, surface exposure in primary forest, frozen conditions, and burial in acidic soil—need to span many years or decades of observation to determine the changing bone characteristics, as has been undertaken in the UK (Armour-Chelu and Andrews 1996).

The author also recommends that the influx of nonhuman remains into medical examiner offices be examined, however cursorily, for their taphonomic alterations (Pokines 2015, 2016). This source of data can give the analyst a much larger sample of large vertebrate remains from the same jurisdiction than the human remains received from the same natural settings and likely remains with a longer temporal span of deposition. These remains are essentially a free source of data about the common taphonomic processes occurring in that region, and taphonomic alterations from these processes likely will be encountered on subsequent human remains recovered.

Forensic taphonomy would be better served by de-emphasis of the word “forensic” in favor of the word “taphonomy”, in the sense that the processes that we observe over the short-term (forensic) interval are also relevant to other researchers in the fields of zooarchaeology, paleoanthropology, and paleontology and are frequently examined by them. Since it is not possible to operate an actualistic taphonomic experiment that proceeds for millennia or longer, researchers from these disciplines necessarily rely upon experiments involving taphonomic processes over the short term, using the uniformitarian principle, to extrapolate processes that may have happened in the unreachable past. It is of primary concern to these other disciplines in what contexts, in what amounts, and in what states bones survive this initial deposition period (roughly equal to the forensic interval), since surviving this gamut before final deposition in a more protected setting (in caves or sediments) is how the majority of bones are preserved to become part of the archaeological and paleontological record (Brain 1980, 1981; Hill 1980; Pokines et al. 2011). The majority of bone destruction and dispersal takes place relatively early during the PMI (often within the first month and certainly within the first few years), and the majority of bones do not survive past this early (necrological) postmortem phase. Slower but persistent processes of destruction make it unlikely that the remaining bone will still be identifiable, if lying exposed, within a few decades. Burial in benign soil can greatly slow bone destruction, but acidic soils can degrade bone until only unanalyzable residue remains (Gordon and Buikstra 1981). All researchers in taphonomy have as a primary concern the initial changes occurring immediately after death, which this volume will examine.

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References

Allison, P. A., and D. E. G. Briggs (eds.) (1991) *Taphonomy: Releasing the Data Locked in the Fossil Record*. Springer, Dordrecht.

American Board of Forensic Anthropology (ABFA) (2021) Application to sit for the certification examination in forensic anthropology. Electronic document, http://theabfa.org/faq/applicants/, accessed 21 January 2021.

Armour-Chelu, M., and P. Andrews (1996) Surface modification of bone from Overton Down, Wiltshire. In *The Experimental Earthwork Project 1960–1992* ed. by M. Bell, P. J. Fowler, and S. W. Hillson, pp. 178–185. Council for British Archaeology, York, UK.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Palaeobiology* 4(2):150–162.

Behrensmeyer, A. K. (1991) Terrestrial vertebrate accumulations. In *Taphonomy: Releasing the Data Locked in the Fossil Record* ed. by P. A. Allison and D. E. G. Briggs, pp. 291–335. Springer, Dordrecht.

Behrensmeyer, A. K., and S. M. Kidwell (1985) Taphonomy's contributions to paleobiology. *Paleobiology* 11(1):105–119.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1991) Recognition of cemetery remains in the forensic setting. *Journal of Forensic Sciences* 36(1):230–237.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1997) Recognition of cemetery remains in the forensic setting. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 165–170. CRC Press, Boca Raton, FL.

Binford, L. R. (1981) *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Binford, L. R., and J. B. Bertram (1977) Bone frequencies and attritional processes. In *For Theory Building in Archaeology* ed. by L. R. Binford, pp. 77–153. Academic Press, New York.

Bonney, H., and A. Goodman (2021) Validity of the use of porcine bone in forensic cut mark studies. *Journal of Forensic Sciences* 66(1):278–284.

Brain, C. K. (1980) Some criteria for the recognition of bone-collecting agencies in African caves. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 107–130. University of Chicago Press, Chicago.

Brain, C. K. (1981) *The Hunters or the Hunted? An Introduction to African Cave Taphonomy*. University of Chicago Press, Chicago.

Buckland, W. (1823) *Reliquiae Diluvianae, or, Observations on the Organic Remains Contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, Attesting to the Action of an Universal Deluge*. J. Murray, London.

Buikstra, J. E., and D. H. Ubelaker (eds.) (1994) *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archeological Survey Research Series No. 44, Fayetteville, AR.

Carson, E. A., V. H. Stefan, and J. F. Powell (2000) Skeletal manifestations of bear scavenging. *Journal of Forensic Sciences* 45(3):515–526.

Christensen, A. M., M. A. Smith, and R. M. Thomas (2012) Validation of X-ray fluorescence spectrometry for determining osseous or dental origin of unknown material. *Journal of Forensic Sciences* 57(1):47–51.

DeBruyn, J. M., K. M. Hoeland, L. S. Taylor, J. D. Stevens, M. A. Moats, S. Bandopadhyay, S. P. Dearth, H. F. Castro, K. K. Hewitt, S. R. Campagna, A. M. Dautartas, G. M. Vidoli, A. Z. Mundorff, and D. W. Steadman (2021) Comparative decomposition of humans and pigs: Soil biogeochemistry, microbial activity and metabolomic profiles. *Frontiers in Microbiology* 11:608856. DOI: 10.3389/fmicb.2020.608856.

Donovan, S. K. (ed.) (1994) *The Palaeobiology of Trace Fossils*. Wiley, Chichester, UK.

Duhig, C. (2003) Non-forensic remains: The use of forensic archaeology, anthropology and burial taphonomy. *Science and Justice* 43(4):211–214.

Efremov, J. A. (1940) Taphonomy: New branch of paleontology. *Pan-American Geologist* 74(2): 81–93.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Fernández-Jalvo, Y., and P. Andrews (2016) *Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification*. Springer, Dordrecht.

Fisher (1995) Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory* 2(1):7–68.

Geberth, V. J. (2006) *Practical Homicide Investigation* (4th ed.). CRC Press, Boca Raton, FL.

Gordon, C. G., and J. E. Buikstra (1981) Soil pH, bone preservation, and sampling bias at mortuary sites. *American Antiquity* 46(3):566–571.

Haglund, W. D. (1997a) Dogs and coyotes: Postmortem involvement with human remains. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 367–381. CRC Press, Boca Raton, FL.

Haglund, W. D. (1997b) Rodents and human remains. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 405–414. CRC Press, Boca Raton, FL.

Haglund, W. D., and M. H. Sorg (eds.) (1997) *Forensic Taphonomy: The Postmortem Fate of Human Remains*. CRC Press, Boca Raton, FL.

Haglund, W. D., and M. H. Sorg (eds.) (2002) *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives*. CRC Press, Boca Raton, FL.

Hill, A. P. (1980) Early postmortem damage to the remains of some contemporary East African mammals. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 131–155. University of Chicago Press, Chicago.

Holland, T., J. Byrd, and V. Sava (2008) Joint POW/MIA Accounting Command's Central Identification Laboratory. In *The Forensic Anthropology Laboratory* ed. by M. W. Warren, H. A. Walsh-Haney, and L. E. Freas, pp. 47–63. CRC Press, Boca Raton, FL.

Hutton, J. (1788) *The Theory of the Earth; or, an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe*. Transactions of the Royal Society of Edinburgh, Vol. 1, Edinburgh, Scotland.

Junod, C. A. (2013) *Subaerial Bone Weathering and Other Taphonomic Changes in a Temperate Climate*. M.S. Thesis, Boston University School of Medicine, Boston.

L'Abbé, E. N., S. A. Symes, J. T. Pokines, L. L. Cabo, K. E. Stull, S. Kuo, D. E. Raymonds, P. S. Randolph-Quinney, and L. R. Berger (2015) Evidence of fatal skeletal injuries on Malapa Hominins 1 and 2. *(Nature) Scientific Reports* 5:15120. DOI: 10.1038/srep15120.

Lloveras, Ll., C. Rissech, and N. Rosado (2016) Tafonomía forense. In *Patología y Antropología Forense de la Muerte: La Investigación Científico-Judicial de la Muerte y la Tortura, desde las Fosas Clandestinas, hasta la Audiencia Pública* ed. by C. Sanabria-Medina, pp. 453–523. Forensic Publisher, Bogotá, Colombia.

Lyell, C. (1830–1833) *Principles of Geology* (3 Vols.). J. Murray, London.

Lyman, R. L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

Lyman, R. L. (2008) *Quantitative Paleozoology*. Cambridge University Press, Cambridge.

Martin, R. E. (1999) *Taphonomy: A Process Approach*. Cambridge University Press, Cambridge.

Matuszewski, S., M. J. R. Hall, G. Moreau, K. G. Schoenly, A. M. Tarone, and M. H. Villet (2020) Pigs vs people: The use of pigs as analogues for humans in forensic entomology and taphonomy research. *International Journal of Legal Medicine* 134:793–810.

Micozzi, M. S. (1991) *Postmortem Change in Human and Animal Remains: A Systematic Approach*. Charles C Thomas, Springfield, IL.

Miller, G. J. (1969) A study of cuts, grooves, and other marks on recent and fossil bones. 1. Animal tooth marks. *Tebiwa* 12:9–19.

Miller, G. J. (1975) A study of cuts, grooves, and other marks on recent and fossil bones. 2. Weathering cracks, fractures, splinters, and other similar natural phenomena. In *Lithic Technology: Making and Using Stone Tools* ed. by E. H. Swanson, Jr., pp. 211–226. Aldine, Chicago.

Morlan, R. E. (1984) Toward the definition of criteria for the recognition of artificial bone alterations. *Quaternary Research* 22(2):160–171.

Nawrocki, S. P. (1995) Taphonomic processes in historic cemeteries. In *Bodies of Evidence: Reconstructing History Through Skeletal Analysis* ed. by A. Grauer, pp. 49–66. Wiley-Liss, New York.

Nielsen-Marsh, C. M., and R. E. M. Hedges (2000) Patterns of diagenesis in bone I: The effects of site environments. *Journal of Archaeological Science* 27(12):1139–1150.

Odell, G. H., and F. Cowan (1987) Estimating tillage effects on artifact distributions. *American Antiquity* 52(3):456–484.

Owsley, D. W., and R. L. Jantz (eds.) (2015) *Kennewick Man: The Scientific Investigation of an Ancient American Skeleton*. Texas A&M University Press, College Station, TX.

Patterson, J. H. (1996) *The Man-Eating Lions of Tsavo*. Field Museum, Chicago.

Payne, S. B. (1983) Bones from cave sites: Who ate what? In *Animals and Archaeology: 1. Hunters and Their Prey* ed. by J. Clutton-Brock and C. Grigson, pp. 149–162. BAR International Series 163, Oxford.

Peterson, R. O. (1977) *Wolf Ecology and Prey Relationships on Isle Royale*. U.S. National Park Service Scientific Monograph Series No. 11, Washington, DC.

Pilloud, M. A., M. S. Megyesi, M. Truffer, and D. Congram (2016) The taphonomy of human remains in a glacial environment. *Forensic Science International* 261:161.e1–161.e8.

Pobiner, B. L. (2007) *Hominin-Carnivore Interactions: Evidence from Modern Carnivore Bone Modification and Early Pleistocene Archaeofaunas (Koobi Fora, Kenya; Olduvai Gorge, Tanzania)*. Ph.D. Dissertation, Rutgers University, Newark, NJ.

Pobiner, B. L., L. Dumouchel, and J. Parkinson (2020) A new semi-quantitative method for coding carnivore chewing damage with an application to modern African lion-damaged bones. *Palaios* 35(7):302–315.

Pokines, J. T. (2009) Forensic recoveries of U.S. war dead and the effects of taphonomy and other site-altering processes. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 141–154. Prentice Hall, Upper Saddle River, NJ.

Pokines, J. T. (2015) Identification of nonhuman remains received in a medical examiner setting. *Journal of Forensic Identification* 65(3):223–246.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T. (2018a) Differential diagnosis of the taphonomic histories of common types of forensic osseous remains. *Journal of Forensic Identification* 68(1):87–145.

Pokines, J. T. (2018b) Two cases of dendrochronology used to corroborate a forensic postmortem interval. *Journal of Forensic Identification* 68(4):457–465.

Pokines, J. T. (2020) The case of the… cases: The flow of the ordinary into a medical examiner's office. In *Case Studies in Forensic Anthropology: Bonified Skeletons* ed. by H. Garvin and N. R. Langley, pp. 291–302. CRC Press, Boca Raton, FL.

Pokines, J. T., N. Appel, C. Pollock, C. J. Eck, A. G. Maki, A. S. Joseph, L. Cadwell, and C. D. Young (2017) Anatomical taphonomy at the source: Alterations to a sample of 84 teaching skulls at a medical school. *Journal of Forensic Identification* 67(4):600–632.

Pokines, J. T., A. Nowell, M. S. Bisson, C. E. Cordova, and C. J. H. Ames (2011) The functioning of a natural faunal trap in a semi-arid environment: Preliminary investigations of WZM-1, a limestone sinkhole site near Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan. *Journal of Taphonomy* 9(2):89–115.

Pokines, J. T., M. M. Udoni, S. Sanders Stark, S. Cassidy, M. L. Atkinson, E. Church, C. L. File, M. K. Green, M. D. Herrera, G. S. Kilroy, B. N. Peace, B. J. Purcell, A. S. Reinman, A. M. Sanchez, and S. J. Springman (2019) Success rates of recovering teeth and infant-sized bones dispersed among leaf litter. *Forensic Anthropology* 2(3):168–177.

Pokines, J. T., D. P. Zinni, and K. Crowley (2016) Taphonomic patterning of cemetery remains received at the Office of the Chief Medical Examiner, Boston, Massachusetts. *Journal of Forensic Sciences* 61(S1):S71–S81.

Quatrehomme, G., A. Lacoste, P. Bailet, G. Grévin, and A. Ollier (1997) Contribution of microscopic plant anatomy to postmortem bone dating. *Journal of Forensic Sciences* 42(1):140–143.

Rogers, T. L. (2005) Recognition of cemetery remains in a forensic context. *Journal of Forensic Sciences* 50(3):5–11.

Ruff, C. B., B. M. Holt, V. Sládek, M. Berner, W. A. Murphy, Jr., D. zur Nedden, H. Seidler, and W. Recheis (2006) Body size, body proportions, and mobility in the Tyrolean "Iceman". *Journal of Human Evolution* 51(1):91–101.

Satish, R. (2020) *Fractography of Fresh vs. Dry Bones*. M.S. Thesis, Boston University School of Medicine, Boston.

Schultz, J., M. Williamson, S. P. Nawrocki, A. Falsetti, and M. Warren (2003) A taphonomic profile to aid in the recognition of human remains from historic and/or cemetery contexts. *Florida Anthropologist* 56(2):141–147.

Shipman, P. (1981) *Life History of a Fossil: An Introduction to Taphonomy and Paleoecology*. Harvard University Press, Cambridge, MA.

Shotwell, J. A. (1955) An approach to the paleoecology of mammals. *Ecology* 36(2):327–337.

Sledzik, P. S., D. Dirkmaat, R. W. Mann, T. D. Holland, A. Zelson Mundorff, B. J. Adams, C. M. Crowder, and F. DePaolo (2009) Disaster victim recovery and identification: Forensic anthropology in the aftermath of September 11. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 289–302. Prentice Hall, Upper Saddle River, NJ.

Steadman, D. W., and H. Worne (2007) Canine scavenging of human remains in an indoor setting. *Forensic Science International* 173:78–82.

Stiner, M. C. (1994) *Honor among Thieves: A Zooarchaeological Study of Neandertal Ecology*. Princeton University Press, Princeton, NJ.

Synstelien, J. A. (2015) *Studies in Taphonomy: Bone and Soft Tissue Modifications by Postmortem Scavengers*. Ph.D. Dissertation, University of Tennessee, Knoxville, TN.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–90. CRC Press, Boca Raton, FL.

Ubelaker, D. H. (2014) Radiocarbon analysis of human remains: A review of forensic applications. *Journal of Forensic Sciences* 59(6):1466–1472.

Ubelaker, D. H., and B. J. Adams (1995) Differentiation of perimortem and postmortem trauma using taphonomic indicators. *Journal of Forensic Sciences* 40(3):509–512.

Ubelaker, D. H., and L. G. Grant (1989) Human skeletal remains: Preservation or reburial? *American Journal of Physical Anthropology* 32(S10):249–287.

Voorhies, M. R. (1969) *Taphonomy and Population Dynamics of an Early Pliocene Vertebrate Fauna, Knox County, Nebraska*. University of Wyoming Contributions to Geology, Special Paper No. 1. Laramie, WY.

Wedel, V. L., and A. Galloway, eds. (2014) *Broken Bones: Anthropological Analysis of Blunt Force Trauma* (2nd ed.). Charles C Thomas, Springfield, IL.

Wedl, C. (1864) Ueber einen Zahnbein und Knochen keimenden Pilz. *Sitzungsbericht der Mathematische Naturwissenschaftliche Classe der Kaiserliche Akademie der Wissenschaften Wien* Band L. K1(1) 50:171–193.

Weigelt, J. (1989 [1927]) *Recent Vertebrate Carcasses and Their Paleobiological Implications*. Reprint edition, translated by J. Schaefer. University of Chicago Press, Chicago.

Wheatley, B. P. (2008) Perimortem or postmortem bone fractures? An experimental study of fracture patterns in deer femora. *Journal of Forensic Sciences* 53(1):69–72.

White, E. M., and L. A. Hannus (1983) Chemical weathering of bone in archaeological soils. *American Antiquity* 48(2):316–322.

Willey, P., and A. Heilman (1987) Estimating time since death using plant roots and stems. *Journal of Forensic Sciences* 32(5):1264–1270.

Willey, P., and L. M. Snyder (1989) Canid modification of human remains: Implications for time-since-death estimations. *Journal of Forensic Sciences* 34(4):894–901.

Microscopic Destruction of Bone

2

MIRANDA M. E. JANS

Contents

He that unburied lies wants not his hearse,
For unto him a tomb's the Universe.

—Sir Thomas Browne
Religio Medici (1642)

Introduction

Skeletal remains are an important resource for biological characteristics of humans and nonhumans in forensic, archaeological, and paleontological settings. Bone is an intricate composite material, containing organic and inorganic components, and a multitude of factors influence its preservation from the moment of death to its recovery and analysis. Bone components (collagen and mineral) initially offer each other mutual protection from degradation, accounting for bone's great preservation potential (Trueman and Martill 2002), but these components are eventually affected by diagenetic processes. *Diagenesis* in bone is defined as postmortem alterations in the physical, chemical, and microstructural composition of bone following its deposition in the environment.

After skeletonization, bones and teeth often survive for a considerable period. Depending on environmental circumstances, this can range between mere decades to millions of years in the case of fossilized remains. Alteration of bones in the burial environment has been studied in detail within archaeological contexts. Smith et al. (2007) identify four main diagenetic pathways: accelerated collagen hydrolysis, bioerosion, dissolution, and fossilization (see also Nielsen-Marsh et al. 2007). Environmental parameters influence degradation of bone, such as rapidly fluctuating water levels and acid soils in a burial site (Nielsen-Marsh et al. 2007). From several studies, it appears that alteration, specifically

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bioerosion, starts early postmortem (Bell et al. 1996; Hedges et al. 1995; Yoshino et al. 1991), making it relevant to the forensic timeframe.

Histology, the study of (thin sections of) tissues and cells using microscopy, is a technique often successfully applied in the case of fragmented and/or burned skeletal remains to identify species (Cuijpers 2006, 2009; Hillier and Bell 2007; Mulhern and Ubelaker 2011) and biological age at death (Cuijpers and Schutkowsky 1993; Streeter 2011). Moreover, bone histology has a long history of use in taphonomic research, which probably started with the research by Wedl on bioerosion of bones and teeth (Wedl 1864). A basic knowledge of histological degradation features is necessary to distinguish diagenesis from pathology. In addition, using histology, different degradation mechanisms can be identified, and bone quality can be (semi-) quantified (Garland 1989; Hedges et al. 1995; Jans 2008; Jans et al. 2002), which makes it useful in archaeological heritage management studies. The macroscopical appearance of bone often does not reflect the extent of diagenetic change that has taken place (Kontopoulos et al. 2016). Histology has been established as an approach in determining bone preservation in the Netherlands (Van Heeringen et al. 2004). In addition, histology is investigated for its potential in sample selection for biomolecular analyses of archaeological material, as there appears to be a relation between bone microstructural and biomolecular preservation (e.g., Gilbert et al. 2005; Haynes et al. 2002; Hollund 2013). As such, it is also relevant to forensic taphonomic analysis. The succession of gross putrefactive stages is well characterized (see Chapter 3, this volume), as are the sequences of different invertebrates that colonize the body postmortem. This serves the purpose of estimating an accurate postmortem interval (PMI), one of the first questions to arise when remains have been located. Similar possibilities exist for histology, focusing, for example, on the sequence of events that marks the processes of skeletonization. The macroscopical preservation of bone is unfortunately not very informative regarding its microstructural or molecular preservation (Garland 1993; Stout 1978). Histology is a technique that is available in most osteological laboratories and can be performed without expensive equipment (Maat et al. 2001), making it suitable as a quick screening or research technique. (For a description of various methods of preparing thin sections of bone, please see Chapter 21.) Important research questions range from determining the rate of decay in different environments to resolving early postmortem history or sample quality evaluation. So far, the effects of taphonomic processes have been primarily studied for bone or its components in the framework of archaeological heritage management or in laboratory situations (see, for example, Nielsen-Marsh and Hedges 1997 and Smith et al. 2007).

The usual view on bone taphonomic processes affecting skeletal remains is that they result in the loss of information on different levels and therefore need to be identified to avoid bias or false interpretation (Chapter 1). Detailed knowledge of taphonomic features or signatures also adds valuable information on the sequence of taphonomic events (Turner-Walker and Jans 2008). In this chapter, the potential of histology in the research of taphonomy will be reviewed. Studying these effects (Chapter 21) in more detail could improve identification of early postmortem history and lead to more accurate estimates of the PMI.

Thin-Section Analysis

To facilitate quantification of alteration and comparison to other possible measurements, a few methods will be described here. The presence or absence of microbial alteration is (semi-) quantified using the *Oxford Histological Index* (OHI) (Hedges et al. 1995; Millard

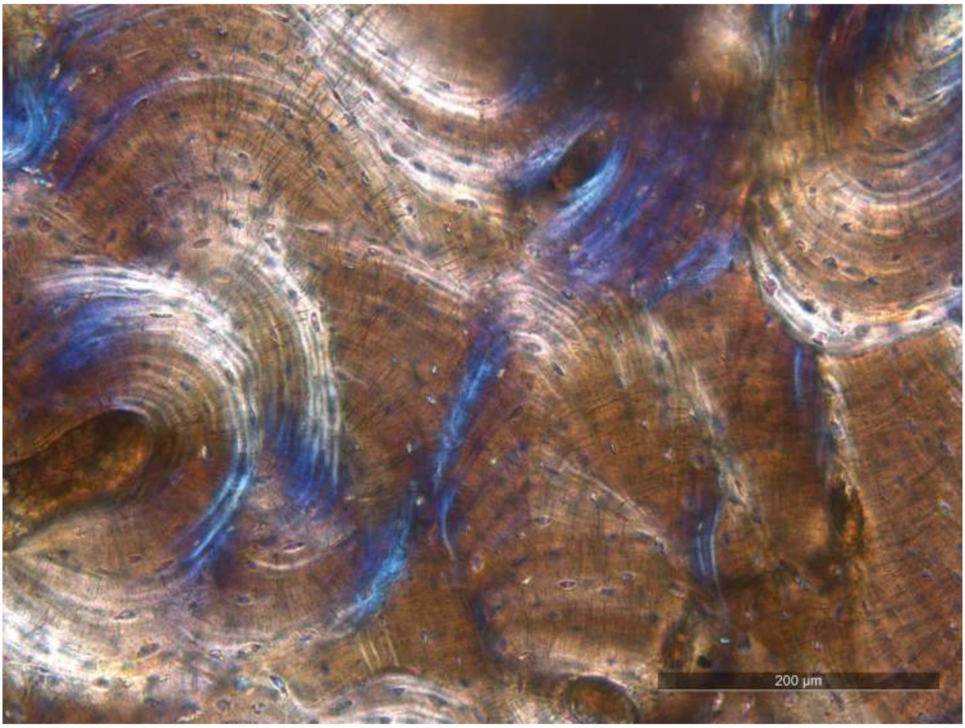

Figure 2.1 Micrograph of a transversal thin section of a human femur (unknown PMI, USA) with well-preserved bone microstructure.

2001). The OHI is a scale of six categories ranging from 5 (pristine bone; Figure 2.1) to 0 (no original bone left). This method also can be applied to thick sections using reflected light. Turner-Walker and Syversen (2002) developed a method quantifying microbial (bacterial) alteration using back-scattered electrons, scanning electron microscope (BSE-SEM) and digital image analysis. This method results in a *Bioerosion Index* (BI), which offers information on the percentage of original bone matrix destroyed by bacterial alteration. This method is more precise than the OHI but has the disadvantage of being more time-consuming as well as analyzing a relatively small portion of the bone.

Using the description of bioerosion morphology by Hackett (1981), it is possible to discern different types of *microscopical focal destructions* (MFD), which were attributed to bacterial or fungal action. In some cases, microorganisms themselves are present and visible in the bone, although these may be different from the organisms that caused the alteration. In most archaeological cases, alteration happened relatively early in the diagenetic history of the bone, and direct evidence of the organisms causing the alteration will have disappeared, save for—perhaps exceptional—cases where fossilized bacteria were found (Baud and Lacotte 1984; Jackes et al. 2001; Pesquero et al. 2010).

Microscopic fissuring of the bone microstructure is hard to quantify, as it is often irregularly spread across the bone, and there are multiple causes that lead to cracking, including specimen preparation. The amount of micro-fissures in bone can be quantified as a percentage of cracked and non-cracked bone *basic structural units* (e.g., osteons; in non-Haversian bone, a grid is used) as described in Jans et al. (2002). A quick indicator of overall histological preservation is provided by determining the generalized histological index (GHI) after Hollund et al. (2012).

Other types of diagenetic change, such as *inclusion* of foreign material in the natural bone pores, *infiltration* of foreign material into the bone matrix (common examples are humic factors or metallic ions), or a decrease in natural *birefringence* of the bone matrix, also can be observed and (semi-) quantified with histology (Jans et al. 2002). The intensity of birefringence of the bone matrix when observed with polarized light can be expressed, for example, as a scale ranging from 1 (comparable to fresh bone), to 0.5 (reduced intensity), to 0 (no birefringence present).

Bioerosion

Microbial alteration is an important pathway for bone degradation (Jans et al. 2004; Smith et al. 2007). *Microbioerosion* of bone (and teeth) has been the focus of several publications over the span of more than 140 years. Microbioerosion in bone can be caused by a range of organisms: fungi (Marchiafava et al. 1974; Wedl 1864), bacteria (Baud and Lacotte 1984; Hackett 1981; Jackes et al. 2001), or microorganisms in aquatic environments (Bell and Elkerton 2008; Bell et al. 1996; Davis 1997; Pesquero et al. 2010; Chapter 7). The morphology of microbial alterations has been described and illustrated in detail by Bell and Elkerton (2008), Davis (1997), Hackett (1981), Pesquero et al. (2010), and Turner-Walker et al. (2002). There are three morphological types of MFD that are attributed to bacteria (Hackett 1981): *linear longitudinal*, *budded*, and *lamellate*. Bacteria produce MFD with a relatively intricate morphology, reorganizing the bone mineral rather than removing it (Jackes et al. 2001). All types of MFD consist of a localized grainy, porous area on the light microscopical level, often surrounded by a hypermineralized cuff (Figure 2.2) ranging in diameter from approximately 10 to 60 µm. High-resolution imaging by BSE-SEM and pore size analysis using mercury intrusion porosimetry (HgIP) reveal that the grainy ultra-structure of bacterial alteration consists of small, connected 0.5–1.0 µm spongiform pores (Jackes et al. 2001; Turner-Walker et al. 2002). Yoshino et al. (1991) found (remains of) bacteria and collagen fibrils in these micropores or vacuoles. They assumed that the spongiform porosity is produced by bacteria and the growth of bacteria, and the extension of tunnels is stopped by deposition of waste products and dissolved mineral (Yoshino et al. 1991).

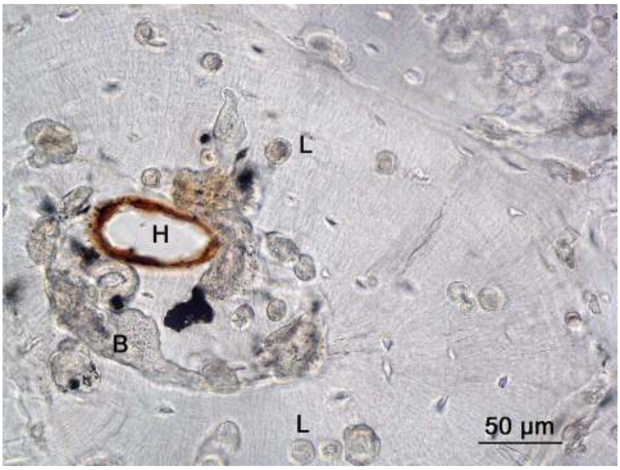

Figure 2.2 Micrograph of a transversal thin section of a human femur (about 60 years post-mortem, North Korea, Korean War). Two different types of bacterial tunneling are present: linear longitudinal (L) and budded (B) tunneling. H: Haversian canal.

Bacterial alteration as viewed in transversal thin sections of bone usually originates from the vascular (Haversian) canals and proceeds by "packing" or filling up of osteons until no original microstructure is left (Hackett 1981). For example, where there is a cementing line surrounding an osteon, this line initially serves as a barrier for further bacterial tunneling (Hackett 1981). Bacterial alteration normally occurs early postmortem, probably in the first decades after death (Hedges et al. 1995; Jans et al. 2004; Yoshino et al. 1991). The earliest documented find of MFD is seven months postmortem; however, this sample was recovered from a predator scat and may not be representative (Bell et al. 1996). Yoshino et al. (1991) found bacterial MFD in bone as soon as five years postmortem. The anatomical arrangement, along with the early postmortem occurrence and the predominance of bacterial alteration in bones derived from graves, suggests that bacterial alteration is perhaps initiated during putrefaction, while soil bacteria may become involved in later stages of decay (Child 1995; Jans et al. 2004).

The first description of fungal alteration of mineralized tissue dates from 1864, when Wedl found branching tunnels approximately 8 μm in diameter in sections of teeth exposed to untreated well water and in fossil reptile teeth. Incidentally, Turner-Walker (2019) suggested that the original tunnels studied by Wedl might in fact have been caused by cyanobacteria or microflora, as the bones were deposited in an aquatic environment. Marchiafava et al. (1974) succeeded in identifying a bone-boring fungus and identified tunneling in bone in an experimental setting. Hackett (1981) named those branching tunnels after Wedl (Figure 2.3). Trueman and Martill (2002) identified a second type of *Wedl tunnel*, characterized by a much smaller diameter (Figure 2.4). This thin microtunneling, or Wedl type 2, was associated in another study to acidic soil environments (Fernández-Jalvo et al. 2010), although in that case it was mostly found in superficial areas in bone. According to Marchiafava et al. (1974), bioerosion by fungi is the result of absorption of solubilized organic and mineral bone components, where substances that attack bone are present inside and outside the fungal membranes. Saprophytic fungi are obligatory aerobic (Carlisle et al. 2001); thus, the presence of fungal alteration of bone is a reliable indicator of the presence of oxygen at the time of the alteration in the burial environment.

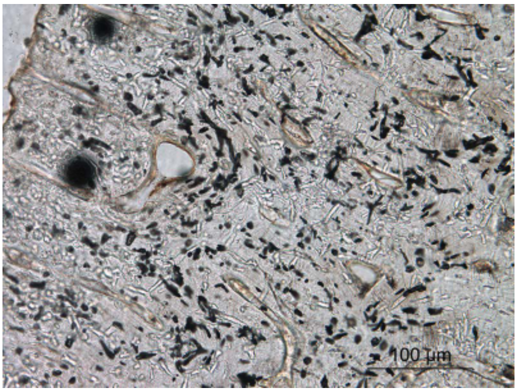

Figure 2.3 Micrograph of a transversal thin section of an animal bone (unknown PMI, Vietnam). Wedl tunneling is present in much of the microstructure. Some tunnels appear dark due to enclosed air in the section.

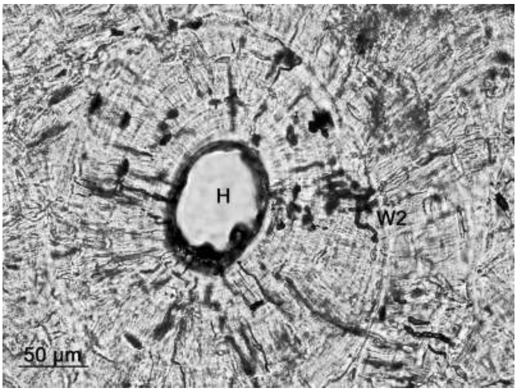

Figure 2.4 Micrograph of a transversal thin section of a human femur (about 65 years postmortem; Palau, WWII). Small branching tunnels are present (W2).

In aquatic environments, typical forms of bioerosion have been found by Bell and Elkerton (2008; cyanobacteria), Davis (1997; algae, fungi, and/or cyanobacteria), and Pesquero et al. (2010; bacteria). Bioerosion in shallow marine as well as freshwater environments is an important diagenetic pathway and occurs soon after deposition (Davis 1997). In an experimental bone deposition study in Southern Florida, USA, in freshwater and marine locations, bioerosion by endolithic cyanobacteria and algae was found on exposed bird bones within 4–15 days (Davis 1997). Superficial borings (about 250 µm in diameter) that meandered parallel to the bone surface were also found in these bones (Davis 1997). This newly described type of bioerosion was named *Hackett tunneling* and is likely caused by cyanobacteria and/or algae (Davis 1997). In this study, it became clear that in these aquatic environments, when bioerosion could occur, it almost always did. Rapid covering with sediment inhibited the process (Davis 1997). MFD caused by cyanobacteria in marine contexts consist of peripheral microborings (similar to the Wedl type) affecting the outer compact layer of the bone, apparently only at light-exposed areas of the bone (Bell and Elkerton 2008; Davis 1997). Slightly different types of MFD have been found by Pesquero et al. (2010) in a lacustrine Miocene site in Spain, where the MFD have a hypermineralized rim and contain internal microspheres, which are probably the fossilized remains of bacteria.

From the above discussion, it becomes clear that early taphonomic conditions influence type and extent of bioerosion. Archaeological studies of bioerosion patterns recording the taphonomic history of bone show promising results. In a study on the preservation of skeletal remains from a Bronze Age site in Cladh Hallan, Scotland, the lack of significant bacterial alteration of bones of a particular skeleton was combined with other data, including a discrepancy in the ^{14}C dating and a different burial context as compared to other skeletal material from that site (Parker Pearson et al. 2005). The collection of anomalies suggested postmortem manipulation, most likely artificial mummification due to the arrested character of the decay of the body (Parker Pearson et al. 2005). Subsequent studies of large samples of archaeological human bone indicated a relationship between bioerosion and whether remains were neonates (which lack an established gut microbiome) had been buried in anoxic environments or had different funerary treatment (Booth 2016, Hollund et al. 2018).

Taphonomic Signatures

Once remains are buried or inhumed, the burial environment will affect the preservation of bone. On both the microscopic and macroscopic scales, bone diagenesis will cause recognizable site-specific features. An important factor influencing the preservation of bone is of course soil pH (Gordon and Buikstra 1981; Nielsen-Marsh et al. 2007). Soils described as corrosive for bone preservation are generally acidic ($pH < 6$), aerated, and well-drained, thereby reducing the capacity for local buffering (Nielsen-Marsh et al. 2007). These circumstances result in poor preservation of bone due to leaching of the bone mineral, which in turn will expose the organic components of bone to further alteration. In addition, these circumstances will exacerbate preexisting microbial damage by collapsing the spongiform pores (Nielsen-Marsh et al. 2007). Corrosive damage can result in *generalized destruction* of the microstructure—a loss of recognizable features—and dissociation of the bone (flaking, Figure 2.5) (Garland 1989). Conversely, a rapid, non-biologically mediated collagen loss, probably due to alternate wetting-drying cycles (Chapter 11) or a strongly alkaline environment, can cause extensive cracking of the bone microstructure as well as loss of natural birefringence (Nielsen-Marsh et al. 2007; Smith et al. 2002).

Bone is a porous material, and, as such, soil components or metals from artifacts can infiltrate the bone matrix (infiltrations) as well as infill the natural bone pores (inclusions) (Garland 1989). In some cases, infiltration of material like copper or humic acids can contribute to the structural, if not biomolecular, preservation of bone by inhibiting the actions of microorganisms (Janaway 1987; Nicholson 1998). In many cases, such infiltration will interfere with biomolecular studies, such as ^{14}C dating (Van Klinken and Hedges 1995). Adipocere, as a product of saponification of fats present in bone (Chapters 3 and 7), can sometimes be preserved in bone pores and the medullar cavity. It is visible as birefringent, almost crystalline structures of variable size (Figure 2.6).

Several minerals are strong indicators for local conditions in the burial environment. For example, the presence of vivianite (Figure 2.7) is indicative of a reducing, anoxic environment (Mann et al. 1998; Chapter 12), as is the presence of manganese oxides (Hollund et al. 2018). Framboidal pyrite can form only in anoxic conditions; when exposed to oxygen, it will corrode (Turner-Walker 1999; Turner-Walker and Jans 2008).

Figure 2.5 Micrograph of a thin section of a human tibia (about 200 years postmortem, USA). Extreme microbial alteration is present on the inside of the bone, with generalized destruction leading to flaking of the outer layers of bone.

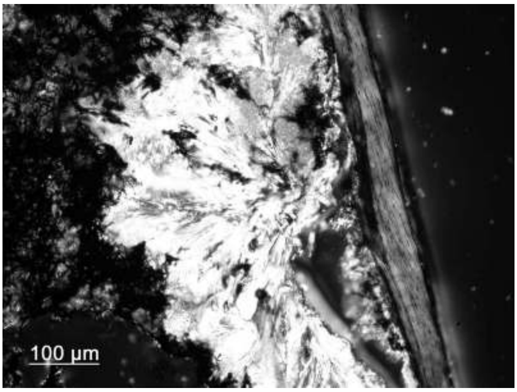

Figure 2.6 Micrograph of a thin section of a human femur (about 65 years postmortem, Papua New Guinea, WWII) showing a thin trabecula of bone with adipocere (polarized light).

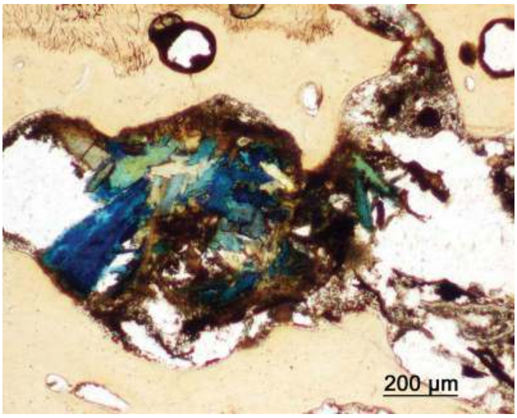

Figure 2.7 Micrograph of a thin section of animal cortical bone (Neolithic, the Netherlands). In a damaged area of the bone, blue crystals (vivianite) are present.

Framboidal pyrite formation is mediated by sulfate-reducing bacteria in anoxic conditions and is often found in marine environments where sulfate is abundant (Turner-Walker 1999). Changes in the oxygen content in the burial environment can cause oxidation of the pyrite, leading to (localized) acidification and damage to the bone structure (Turner-Walker 1998).

Although morphology and color of minerals are diagnostic in microscopy, SEM-EDS is a very useful technique to identify exactly the composition of inclusions and infiltrations. Knowledge and identification of these inclusions are important, because they not only can inform on the (micro-) environment of buried bone but can also mimic biological structures (Kaye et al. 2008). Turner-Walker and Jans (2008) as well as Hollund et al. (2012) and Hollund et al. (2018) related certain characteristic diagenetic signatures in bone to sequences of taphonomic events in selected, well-documented archaeological sites. The environmental taphonomic signatures in bone can thus inform on changing environmental conditions or illustrate local stratigraphic conditions (Turner-Walker and Jans 2008; Wilkin et al. 1996).

Temperature

Alteration of the bone material by (extreme) temperatures has been described abundantly in the literature with a focus mainly on color changes but also on cracking and fragmentation patterns (Schmidt and Symes 2015). On the macroscopical level, color changes are a well-established indicator of thermal exposure. These color data are important, as time of heat exposure and temperature will alter the bone and can cause significant loss of information (Chapter 14). Color as an indicator for specific temperatures/durations of exposure, however, is problematic in histology, as color intensity and hue are influenced by light source, section thickness, and perception of the researcher (Hanson and Cain 2007). Bone heated while fully fleshed and for the purpose of food preparation (cooking, roasting, etc.) does not show histological change as described by several previous studies (Hanson and Cain 2007; Roberts et al. 2002). Transmission electron microscopy analysis of structural changes in collagen fibers can be used to detect low-level heating as described by Koon et al. (2003). This method has proven reliable in sorting cooked and non-cooked archaeological bone (Koon et al. 2008).

In addition to color change and incorporation of carbon (which is again lost with increasing temperatures), another histological indicator of thermal alteration is cracks emanating from the Haversian canals (Brain 1993; Hanson and Cain 2007). Hanson and Cain (2007) also found other types of cracks; however, as these were also present in unburned archaeological bone, it is unclear whether they were caused by (later) diagenetic processes (Figure 2.8). Although these types of cracks could in some cases confuse the interpretation of microstructure in species determination studies, generally they are of little influence on the interpretation of bone histology (Cuijpers 2006).

Few studies have been performed on the effect of freezing or freezing-thawing cycles on bone histology. Tersigni (2007) investigated the effect of freezing on bone segments but found no statistically significant effect or trend (e.g., change in size of Haversian canals

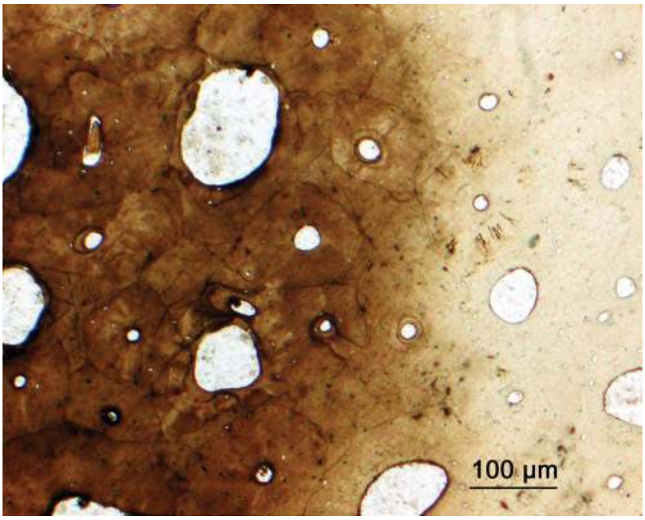

Figure 2.8 Micrograph of a thin section of cortical nonhuman animal bone (Neolithic, the Netherlands). The bone was partially burned and the burned area in the section shows cracking, and a difference in color compared to the unburned area.

or osteocyte lacunae). However, using SEM, cracks were found originating from the Haversian canals that were not found in unfrozen samples. These are somewhat smaller than the cracks caused by heating, as discussed earlier. A possible explanation for these cracks is ice expansion in the bone pores, affecting the structural integrity of the surrounding bone matrix (Chapter 11). In the case of fresh bone with adhering soft tissue, this could be expansion of moisture in the blood vessels permeating the bone (Tersigni 2007). From the results of this study, it does not appear that freezing damage would impair histological analysis of the sample, but it is also hard to recognize, as the signature is similar to thermal alteration and other diagenetic changes.

Case Studies

Swifterbant, the Netherlands

Swifterbant (Flevoland, the Netherlands) is a unique early Neolithic Dutch site discovered in the 1960s, and excavation of part of the site yielded a wealth of archaeological material including human burials (Huisman et al. 2008, 2009). The burial environment at Swifterbant currently is changing due to lowering of the groundwater table for agricultural activities. During an excavation in 2005, bone samples were taken while environmental parameters were monitored to assess whether the rate or mechanism of degradation had changed (Huisman et al. 2008). In a case with such a long taphonomic history, it is essential to determine the timing of the decay signatures that are present, as the local burial environment (e.g., ground water level and quality) will have varied in the past.

The 15 Swifterbant bone samples all consist of fragmented nonhuman animal bone and tooth remains found in the site refuse layer. Two samples were burned (Figure 2.7). Thin sections were prepared by impregnating small samples and fragments with Concresive EP2055 (BASF). After hardening they were cut and then ground with a diamond grinding wheel on a Jacobson 618 grinding machine. The sections were mounted on glass slides using Araldite D and Hardener REN HY 956 (Huntsman) and finally ground to a thickness of 30–50 µm. Of the 15 samples, two show fungal tunneling (Table 2.1). None of the samples show bacterial alteration. Five samples contain well-preserved framboidal pyrite crystals. In one of the samples, a vivianite crystal is present (Figure 2.6). Most samples lack any birefringence.

Fungal alteration of the bone (and teeth) likely occurred early in the site's history. The presence of unoxidized framboidal pyrite indicates that at least locally the environment remained reducing and anoxic, making it unsuitable for fungal activity. If the circumstances were to change, the presence of pyrite may cause additional preservation problems, as oxidation of pyrite results in the formation of sulfuric acid. This acid formation should be buffered by the relatively high concentration of calcium present in this burial environment (Huisman et al. 2008). Much of the cracking (certainly in the case of the burned bone) probably took place earlier in the burial history of the bones. Many of the cracks are filled in with soil material and pyrite. As too little is known of the stratigraphic history of these samples or the site history, it is impossible to say exactly when this happened. The lack of birefringence was probably caused by the long postmortem period, allowing for, among other factors, significant collagen decay due to hydrolysis. To ensure the preservation of the important archaeological heritage at Swifterbant, it is essential that environmental

Table 2.1 **Histological Analysis of the Swifterbant Bone Remains**

Sample	OHI	Fungal	Bacterial	Cracking (%)	Birefringence
56110	1	1	0	0%	0
56109	5	0	0	20%	0
56107	5	0	0	No data	0.5
56108	4	1	0	No data	0
56102	5	0	0	10%	0.5
56103	5	0	0	75%	0
56104	5	0	0	20%	0
56105	5	0	0	20%	0
56106	5	0	0	20%	0
56111	5	0	0	40%	0
56112	5	0	0	20%	0
56113	5	0	0	10%	0
56114	5	0	0	10%	0
56115	5	0	0	10%	0.5
56116	5	0	0	40%	0.5

parameters are monitored closely as further environmental change may challenge the buffering capacity for preservation exhibited by this rich site.

Anthropological Research Facility, University of Tennessee

Several studies suggested that normally, bacterial degradation takes place within the first 100 years postmortem, most of it possibly occurring during putrefaction (Child 1995; Hedges et al. 1995; Jans et al. 2004; Yoshino et al. 1991). The Anthropological Research Facility (ARF) of the University of Tennessee is located in Knoxville and has generated a great deal of data relevant to this question (Chapter 3). After degradation, bones are usually harvested to become part of the W. M. Bass Donated Skeletal collection (Klippel and Synstelien 2007). The facility provides a unique opportunity to study decay and monitor the depositional environment in great detail. To investigate histological bone preservation in the early postmortem timeframe, ribs (11th or 12th) were taken from 14 bodies decomposed at different locations on the ARF terrain. Care was taken to sample remains in different stages of decay to represent a spectrum of degradation, and the PMI of the remains ranged from 10 days to four years. Overall, the rate of macroscopical decay was fairly quick, showing advanced decomposition stages and partial skeletonization within a few weeks postmortem, and after one year, all samples were either mummified or skeletonized. After describing and photographing the remains, any remaining soft tissue and debris were removed, and the bone was put in a polystyrene bag and stored in a cool and dark place until it could be frozen at –20°C.

From the ribs, samples were taken for histology using a Dremel® tool. Histological sections were prepared manually according to the improved Frost's technique (Chapter 21). After grinding, the section was cleaned in distilled water and dried overnight between layers of tissue paper. The section was mounted on a glass slide using Permount (Fisher Scientific) and was ready for analysis using normal transmitted light and polarized light microscopy.

Table 2.2 Description of Samples

Sample	OHI	PMI (months)	Adipocere
A	5	49	0
B	5	46	0
C	5	25	0.5
D	5	23	0.5
E	5	12	0.5
F	5	18	0.5
G	5	12	0.5
H	5	12	1
I	5	10	0.5
J	5	8	1
K	5	7	1
L	5	2	1
M	5	1	1
N	5	1	0

Note: All samples taken consisted of ribs (number 11 or 12).

Histologically, the samples were very well preserved (Table 2.2). The only observable diagenetic feature was the presence of adipocere, which was included in the bone pores, even in samples where macroscopically no adipocere was visible. The amount of adipocere present in a bone section decreased with increasing PMI. There was no adipocere visible in both four-year-old samples, while samples exposed between 12 and 24 months showed generally intermediate amounts of adipocere (only some present in scattered Haversian canals or osteocyte lacunae). All but two samples younger than 12 months showed large amounts of adipocere (present in Haversian canals, osteocyte lacunae, and medullary area). Sample N, for example, had been exposed for only 10 days but had been completely skeletonized by invertebrate activity, so presumably there had not been enough time for adipocere formation.

The lack of microbial alteration is surprising and has several possible explanations. One possibility is that the microbes responsible for (initial) bone alteration are anaerobic, and decay in an oxygen-rich environment simply is too fast for a prolonged anaerobic putrefaction stage such as would occur in a coffin burial. Most, if not all, human samples from the study by Jans et al. (2004) were inhumed, many of those in coffins. Moreover, some of the bodies, especially those deposited in summer, skeletonized exceptionally quickly. The skeletons are not protected from small vertebrate scavengers or invertebrates, which results in a rapid removal of soft tissue. The remains appear to be in advanced decomposition stages, and skeletonization occurs within weeks to a month of deposition (in summer), before significant bacterial degradation can take place. After the fast putrefaction, the bones dry out quickly, inhibiting further bacterial action. More research is clearly needed, comparing early decay of surface-exposed remains to buried remains in varying circumstances.

Conclusions and Future Research

Diagenetic alteration can destroy bone microstructure, which interferes with (histological) analyses such as age or species determination (e.g., Cuijpers 2006). Knowledge of the different types of alteration is essential to avoid confusion with pathological changes in bone (Bell 1990). Decomposition can affect bone quality extensively, impeding biomolecular analyses. Histology is a technique for quick sample evaluations, aiding in sample selection, and it has the potential to identify well-preserved areas within a single bone. In addition, precisely because peri- and postmortem events leave behind recognizable signatures in bone microstructure, taphonomical histories can be reconstructed (Chapter 20). Not only is material from the environment included in natural bone pores, but formation of different minerals is also useful as indicators of (past) microenvironmental conditions. Bioerosion types are indicative for burial or deposition in different (aquatic) environments or for the presence of oxygen in the environment (fungi). The presence or absence of bacterial alteration of bone has been linked, in archaeological studies, to early postmortem treatment of the remains (fragmentation, defleshing, or complete burial).

All the existing data notwithstanding, further research is clearly needed on this topic. Experiments, consisting of degradation of specific material in controlled or well-characterized environments, are needed to bring this study forward from a field based on observation of trends and patterns of alteration in different burial environments. The sequence, rate, and cause of taphonomic signatures can be firmly established only when factors influencing preservation are isolated using experimental control or detailed observation of the burial environment throughout the experiment. Identifying specific (sequences of) bioeroding microorganisms for PMI determination will require experimental approaches such as practiced in the ARF or as showcased in the Neuadd experimental burials (Fernández-Jalvo et al. 2010) and the experimental bird bone deposition by Davis (1997). Experiments must include different (micro-) environments as well as different climates. The focus of such studies could, for example, be on differences in bioerosion in defleshed, exposed, or buried material, and may include protective textiles, such as in the taphonomic study by Kontopoulos et al. (2016). Similar experiments would be necessary to establish detailed knowledge of the speed of diagenetic processes in different environments, important in archaeological heritage management as well as PMI determination. Useful information on the rate of diagenesis already has been obtained by comparing the preservation of archaeological bones excavated from the same site but deposited at different points in time (e.g., Van Heeringen et al. 2004). In addition, it has become clear that diagenesis continues even when bone is in storage and can result in significant and fast loss of (molecular) information (Pruvost et al. 2007). As much material from ongoing and past taphonomic studies is potentially available in the original experimental settings or in storage, relevant samples for analysis may be obtained with relatively little investment. An example of promising work in this respect is the study by Emmons et al. (2020) using DNA extracts from bone sampled at the ARF to identify which microorganisms colonize skeletal remains identifying inter- and intra-individual variation. The study of the microbiome of death also makes it necessary to repeat some of the earliest diagenetic experiments (like Wedl's) as now we can identify the organisms involved by DNA (Turner-Walker 2019).

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References

Baud, C. A., and D. Lacotte (1984) Étude au microscope électronique à transmission de la colonisation bactérienne de l'os mort. *Comptes Rendus de l'Académie des Sciences* 298:507–510.

Bell, L. S. (1990) Paleopathology and diagenesis: A SEM evaluation of structural changes using backscattered electron imaging. *Journal of Archaeological Science* 17(1):85–102.

Bell, L. S., and A. Elkerton (2008) Unique marine taphonomy in human skeletal material recovered from the medieval warship *Mary Rose*. *International Journal of Osteoarchaeology* 18(5):523–535.

Bell, L. S., M. F. Skinner, and S. J. Jones (1996) The speed of postmortem change to the human skeleton and its taphonomic significance. *Forensic Science International* 82(2):129–140.

Booth, T. J. (2016) An investigation into the relationship between funerary treatment and bacterial bioerosion in European archaeological human bone. *Archaeometry* 58(3):484–499.

Brain, C. K. (1993) The occurrence of burnt bones at Swartkrans and their implications for the control of fire by early hominids. In *Swartkrans: A Cave's Chronicle of Early Man* ed. by C. K. Brain, pp. 229–242. Transvaal Museum, Pretoria, South Africa.

Carlisle, M. J., S. C. Watkinson, and G. W. Gooday (2001) *The Fungi*. Academic Press, New York.

Child, A. M. (1995) Towards an understanding of the microbial decomposition of archaeological bone in the burial environment. *Journal of Archaeological Science* 22(2):165–174.

Cuijpers, A. F. G. M. (2006) Histological identification of bone fragments in archaeology: Telling humans apart from horses and cattle. *International Journal of Osteoarchaeology* 16(6):465–480.

Cuijpers, A. F. G. M. (2009) The application of bone histology for species identification in archaeology; With a photo catalogue. *Geoarchaeological and Bioarchaeological Studies* 12. Institute for Geo and Bioarchaeology, Vrije Universiteit, Amsterdam.

Cuijpers, A. G. F. M., and H. Schutkowsky (1993) Histological age determination of the cremated human bones from the urnfields of Deventer-'t Bramelt and Markelo Friezenberg. *Helinium XXXIII* 1:99–107.

Davis, P. G. (1997) Bioerosion of bird bones. *International Journal of Osteoarchaeology* 7(4):388–401.

Emmons, A. L., A. Z. Mundorff, S. W. Keenan, J. Davoren, J. Andronowski, D. O. Carter, and J. M. DeBruyn (2020) Characterizing the postmortem human bone microbiome from surface-decomposed remains. *PLoS ONE* 15:e0218636. DOI: 10.1371/journal.pone.0218636.

Fernández-Jalvo, Y., P. Andrews, D. Pesquero, C. Smith, D. Marín-Monfort, B. Sánchez, E. Geigl, and A. Alonso (2010) Early bone diagenesis in temperate environments. Part I: Surface features and histology. *Palaeogeography, Palaeoclimatology, Palaeoecology* 288(1–4):62–81.

Garland, A. N. (1989) Microscopical analysis of fossil bone. *Applied Geochemistry* 4(3):215–229.

Garland, A. N. (1993) A histological study of archaeological bone decomposition. In *Histology of Ancient Human Bone: Methods and Diagnosis* ed. by G. Grupe and A. N. Garland, pp. 109–126. Springer, Berlin.

Gilbert, M. T. P., L. Rudbeck, E. Willerslev, A. J. Hansen, C. Smith, K. Penkman, K. Prangenberg, C. M. Nielsen-Marsh, M. E. Jans, P. Arthur, N. Lynnerup, G. Turner-Walker, M. Biddle, B. Kjølbye-Biddle, and M. J. Collins (2005) Biochemical and physical correlates of DNA contamination in archaeological bones and teeth. *Journal of Archaeological Science* 32(5):785–793.

Gordon, C. C., and J. E. Buikstra (1981) Soil pH, bone preservation, and sampling bias at mortuary sites. *American Antiquity* 46(3):566–571.

Hackett, C. J. (1981) Microscopical focal destruction (tunnels) in exhumed human bones. *Medicine, Science and the Law* 21(4):243–265.

Hanson, M., and C. R. Cain (2007) Examining histology to identify burned bone. *Journal of Archaeological Science* 34(11):1902–1913.

Haynes, S., J. B. Searle, A. Bretman, and K. M. Dobney (2002) Bone preservation and ancient DNA: The application of screening methods for predicting DNA survival. *Journal of Archaeological Science* 29(6):585–592.

Hedges, R. E. M., A. R. Millard, and A. W. G. Pike (1995) Measurements and relationships of diagenetic alteration of bone from three archaeological sites. *Journal of Archaeological Science* 22(2):201–209.

Hillier, M. L., and L. S. Bell (2007) Differentiating human bone from animal bone: A review of histological methods. *Journal of Forensic Sciences* 52(2):249–263.

Hollund, H. I. (2013) Diagenetic screening of bone samples: Tools to aid taphonomic and archaeometric investigations. *Geoarchaeological and Bioarchaeological Studies* 15. VU University, Amsterdam.

Hollund, H. I., M. Blank, and K. G. Sjögren (2018) Dead and buried? Variation in post-mortem histories revealed through histotaphonomic characterisation of human bone from megalithic graves in Sweden. *PLoS ONE* 13(10):e0204662. DOI: 10.1371/journal.pone.0204662.

Hollund, H. I., M. M. E. Jans, M. J. Collins, H. Kars, I. Joosten, and S. M. Kars (2012) What happened here? Bone histology as a tool in decoding the post-mortem histories of archaeological bone from Castricum, the Netherlands. *International Journal of Osteoarchaeology* 22(5): 537–548.

Huisman, D. J., A. G. Jongmans, and D. C. M. Raemaekers (2009) Investigating Neolithic land use in Swifterbant (NL) using micromorphological techniques. *Catena* 78(3):185–197.

Huisman, D. J., A. Smit, M. M. E. Jans, W. Prummel, A. G. F. M. Cuijpers, and J. H. M. Peeters (2008) Het bodemmilieu op de archeologische vindplaatsen bij Swifterbant (provincie Flevoland): Bedreigingen en mogelijkheden voor in situ behoud. *Rapportage Archeologische Monumentenzorg* 163. RACM, Amersfoort, the Netherlands.

Jackes, M., R. Sherburne, D. Lubell, C. Barker, and M. Wayman (2001) Destruction of the microstructure in archaeological bone: A case study from Portugal. *International Journal of Osteoarchaeology* 11(6):387–399.

Janaway, R. C. (1987) The preservation of organic materials in association with metal artefacts deposited in inhumation graves. In *Death, Decay and Reconstruction: Approaches to Archaeology and Forensic Science* ed. by A. Boddington, A. N. Garland, and R. C. Janaway. Manchester University Press, Manchester, UK.

Jans M. M. E. (2008) Micro-bioerosion of bone: A review. In *Current Developments in Bioerosion* ed. by L. Tapanila and M. Wisshak. Erlangen Earth Science Conferences, Springer Verlag, Berlin.

Jans, M. M. E., H. Kars, C. M. Nielsen-Marsh, C. I. Smith, A. G. Nord, P. Arthur, and N. Earl (2002) In situ preservation of archaeological bone: A histological study within a multidisciplinary approach. *Archaeometry* 44(3):343–352.

Jans, M. M. E., C. M. Nielsen-Marsh, C. I. Smith, M. J. Collins, and H. Kars (2004) Characterisation of microbial attack on archaeological bone. *Journal of Archaeological Science* 31(1):87–95.

Kaye, T. G., G. Gaugler, and Z. Sawlowicz (2008) Dinosaurian soft tissues interpreted as bacterial biofilms. *PLoS ONE* 3:e2808. DOI: 10.1371/journal.pone.0002808.

Klippel, W. E., and J. A. Synstelien (2007) Rodents as taphonomic agents: Bone gnawing by brown rats and gray squirrels. *Journal of Forensic Sciences* 52(4):765–773.

Kontopoulos, I., P. Nystrom, and L. White (2016) Experimental taphonomy: Post-mortem microstructural modifications in Sus scrofa domesticus bone. *Forensic Science International* 266:320–328.

Koon, H. E. C., R. A. Nicholson, and M. J. Collins (2003) A practical approach to the identification of low temperature heated bone using TEM. *Journal of Archaeological Science* 30(11):1393–1399.

Koon, H. E. C., T. P. O'Connor, and M. J. Collins (2008) Sorting the butchered from the boiled. *Journal of Archaeological Science* 37(1):62–67.

Maat, G. J. R., R. P. M. Van Den Bos, and M. J. Aarents (2001) Manual preparation of ground sections for the microscopy of bone tissue: Update and modification of Frost's 'rapid manual method'. *International Journal of Osteoarchaeology* 11(5):366–374.

Mann, R. W., M. E. Feather, C. S. Tumosa, T. D. Holland, and K. N. Schneider (1998) A blue encrustation found on skeletal remains of Americans missing in action in Vietnam. *Forensic Science International* 97(2–3):79–86.

Marchiafava, V., E. Bonucci, and A. Ascenzi (1974) Fungal osteoclasia: A model of dead bone resorption. *Calcified Tissue Research* 14(3):195–210.

Millard, A. R. (2001) The deterioration of bone. In *Handbook of Archaeological Science* ed. by A. M. Pollard and D. R. Brothwell, pp. 637–647. Wiley, New York.

Mulhern, D., and D. Ubelaker (2011) Differentiating human from non-human bone microstructure. In *Bone histology: An Anthropological Perspective* ed. by C. Crowder and S. Stout, pp. 135–152. CRC Press, Boca Raton, FL.

Nicholson, R. A. (1998) Bone degradation in a compost heap. *Journal of Archaeological Science* 25(5):393–403.

Nielsen-Marsh, C. M., and R. E. M. Hedges (1997) Dissolution experiments on modern and diagenetically altered bone and the effect on the infrared splitting factor. *Bulletin de la Société Géologique de France* 168(4):485–490.

Nielsen-Marsh, C. M., C. I. Smith, M. M. E. Jans, A. Nord, H. Kars, and M. J. Collins (2007) Bone diagenesis in the European Holocene II: Taphonomic and environmental considerations. *Journal of Archaeological Science* 34(9):1523–1531.

Parker Pearson, M., A. Chamberlain, O. Craig, P. Marshall, J. Mulville, H. Smith, C. Chenery, M. Collins, G. Cook, G. Craig, J. Evans, J. Hiller, J.-L. Montgomery, G. Taylor, and T. Wess (2005) Evidence for mummification in Bronze Age Britain. *Antiquity* 79(305):529–546.

Pesquero, M. D., C. Ascaso, Y. Fernández-Jalvo, and L. Alcalá (2010) A new taphonomic bioerosion in a Miocene lakeshore environment. *Palaeogeography, Palaeoclimatology, Palaeoecology* 295(1–2):192–198.

Pruvost, M., R. Schwarz, V. Bessa Correia, S. Champlot, S. Braguier, N. Morel, Y. Fernández-Jalvo, T. Grange, and E.-M. Geigl (2007) Freshly excavated fossil bones are best for amplification of ancient DNA. *Proceedings of the National Academy of Sciences of the United States of America* 104(3):739–744.

Roberts, J. P., C. I. Smith, A. M. Millard, and M. J. Collins (2002) The taphonomy of cooked bone: Characterising boiling and its physico-chemical effects. *Archaeometry* 44(3):485–494.

Schmidt, C. W., and S. A. Symes (eds.) (2015) *The Analysis of Burned Human Remains* (2nd ed.). Academic Press, London.

Smith, C. I., C. M. Nielsen-Marsh, M. M. E. Jans, P. Arthur, A. G. Nord, and M. J. Collins (2002) The strange case of Apigliano: Early fossilisation of Medieval bone in Southern Italy. *Archaeometry* 44(3):405–416.

Smith, C. I., C. M. Nielsen-Marsh, M. M. E. Jans, and M. J. Collins (2007) Bone diagenesis in the European Holocene I: Patterns and mechanisms. *Journal of Archaeological Science* 34(9):1485–1493.

Stout, S. D. (1978) Histological structure and its preservation in ancient bone. *Current Anthropology* 19(3):601–604.

Streeter, M. (2011) Histological age at death estimation. In *Bone Histology: An Anthropological Perspective* ed. by C. Crowder and S. Stout, pp. 135–152. CRC Press, Boca Raton, FL.

Tersigni, M. A. (2007) Frozen human bone: A microscopic investigation. *Journal of Forensic Sciences* 52(1):16–20.

Trueman, C. N., and D. M. Martill (2002) The long-term survival of bone: The role of bioerosion. *Archaeometry* 44(3):371–382.

Turner-Walker, G. (1998) The West Runton fossil elephant: A pre-conservation evaluation of its condition, chemistry and burial environment. *The Conservator* 22(1):26–35.

Turner-Walker, G. (1999) Pyrite and bone diagenesis in terrestrial sediments: Evidence from the West Runton freshwater bed. *Bulletin of the Geological Society of Norfolk* 48:3–26.

Turner-Walker, G. (2019) Light at the end of the tunnels? The origins of microbial bioerosion in mineralised collagen. *Palaeogeography, Palaeoclimatology, Palaeoecology* 529:24–38.

Turner-Walker, G., and M. M. E. Jans (2008) Reconstructing taphonomic histories using histological analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 266:227–235.

Turner-Walker, G., C. M. Nielsen-Marsh, U. Syversen, H. Kars, and M. J. Collins (2002) Sub-micron spongiform porosity is the major ultra-structural alteration occurring in archaeological bone. *International Journal of Osteoarchaeology* 12(6):407–414.

Turner-Walker, G., and U. Syversen (2002) Quantifying histological changes in archaeological bones using BSE-SEM image analysis. *Archaeometry* 44(3):461–468.

Van Heeringen, R. M., G. Mauro, and A. Smit (eds.) (2004) A pilot study on the monitoring of the physical quality of three archaeological sites on the UNESCO Monument of Schokland, province of Flevoland, the Netherlands. *Nederlandse Archeologische Rapporten* 26, Rijksdienst voor het Oudheidkundig Bodemonderzoek, Amersfoort, the Netherlands.

Van Klinken, G. J., and R. E. M. Hedges (1995) Experiments on collagen-humic interactions: Speed of humic uptake, and effects of diverse chemical treatments. *Journal of Archaeological Science* 22(2):263–270.

Wedl, C. (1864) Ueber einen Zahnbein und Knochen keimenden Pilz. *Sitzungsbericht der Mathematische Naturwissenschaftliche Classe der Kaiserliche Akademie der Wissenschaften Wien* Band L. K1 (1) 50:171–193.

Wilkin, R. T., H. L. Barnes, and S. L. Brantley (1996) The size distribution of framboidal pyrite in modern sediments: An indicator of redox conditions. *Geochimica et Cosmochimica Acta* 60(20):3897–3912.

Yoshino, M., T. Kimijima, S. Miyasaka, H. Sato, and S. Seta (1991) Microscopical study on time since death in skeletal remains. *Forensic Science International* 49(2):143–158.

Soft Tissue Decomposition in Terrestrial Ecosystems

3

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Contents

Introduction

Vertebrates reportedly contribute less than 1% of the total biomass in a number of terrestrial systems (Barton et al. 2019). Though this is relatively small compared to biomass contributions from plants and microbes, when this vertebrate biomass becomes detritus, it

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has important short-term and long-term ecological effects that have been observed in soil and plant ecology after two (Singh et al. 2018) and five years of decomposition (Barton et al. 2016). With a low carbon-to-nitrogen ratio, decomposing heterotrophic biomass or carrion acts as a high-quality and ephemeral nutrient resource hotspot that can support a dynamic ecological community composed of vertebrate and invertebrate scavengers and microbes (Carter et al. 2007), often referred to as the necrobiome (Benbow et al. 2013). While this is interesting from an ecological perspective, understanding carrion and human decomposition, and the physical, chemical, cultural, and biological processes that influence them, has been at the forefront of research in the fields of archaeology and forensic anthropology. Questions related to site reconstruction, postmortem event reconstruction, postmortem interval (PMI), trauma (antemortem, perimortem, or postmortem), burial location, and cause/manner of death are informed by our understanding of natural decomposition processes and the factors, intrinsic and extrinsic, that contribute to differences in decay (Janaway et al. 2009; Ubelaker 1997).

In fact, the establishment of the first forensic anthropology outdoor decomposition research facility in 1981 was inspired by a real forensic case that exposed how little was known regarding human decomposition (Vidoli et al. 2017). When Dr. William M. Bass, a renowned forensic anthropologist, was pressed on the PMI of remains recovered from a disturbed burial, he initially estimated 6-12 months. It was only later that Dr. Bass discovered that the remains were those of a Confederate soldier named Colonel William Shy. Thanks to embalming and the preservative environment of a then-collapsed cast iron coffin, Dr. Bass was off in his PMI estimation by 112 years, prompting him to propose the establishment of the first human decomposition research facility in Knoxville, TN, USA (Vidoli et al. 2017; Wilson-Taylor and Dautartas 2017).

The present chapter reviews the basics of terrestrial human and other vertebrate decomposition from death to skeletonization and the biological, environmental, behavioral, and cultural factors that impact the decay process. Little attention will be given to post-skeletal processes such as skeletal diagenesis and other processes causing the breakdown of bone (see Chapters 2, 4, 5, 9, and 11, this volume). To complement this review, this chapter includes a discussion on PMI estimation methods.

Studying Decomposition

Death and decay have been the focus of scientists for centuries, but it was not until the 1940s that the term "taphonomy" originated in research related to postmortem processes. Coined by a paleontologist (Efremov 1940), taphonomy refers to the "laws of burial" (Haglund and Sorg 1997a) but can more aptly be defined as the study of postmortem processes related to "the preservation, observation, or recovery of dead organisms", "the reconstruction of their biology or ecology", or "the reconstruction of the circumstances of their death" (Haglund and Sorg 1997b:13). Therefore, the study of decomposition, as an important component of taphonomy, is inherently multidisciplinary, involving such disciplines as anthropology, entomology, chemistry, microbiology, and molecular biology, among others (Chapter 1).

Taphonomy and questions related to taphonomic processes are empirically studied using controlled and semi-controlled methodologies (e.g., laboratory and field-based, respectively) and uncontrolled methodologies (e.g., collaborating directly with medical examiners on forensic cases and/or using forensic case reports retrospectively) (Varlet et al. 2020). Under special circumstances, case studies themselves have also been illuminating (e.g., Rathbun and Rathbun 1984; Schotsmans et al. 2011; Steadman and Worne 2007; Zhou and Byard 2010). The rise of taphonomic research facilities, in particular, has influenced a fundamental shift in decomposition research, providing researchers somewhat greater control over factors and variables of interest while also fostering interdisciplinary research (Wescott 2018). Field-based methodologies at these facilities generally use actualistic modeling, which is immersed in the theory of uniformitarianism (Haglund and Sorg 1997b; Chapter 1). In this type of modeling, hypotheses regarding specific variables are tested while monitoring environmental covariates, and results and observations are applied to real-world scenarios. While there are a number of taphonomic facilities that utilize animal analogs for human decomposition (e.g., University of Central Lancashire's Taphonomic Research in Anthropology: Centre for Experimental Studies, TRACES), there is an ever-growing number of taphonomic research facilities that are human-centric, benefiting from body donation programs (Wescott 2018). There are currently 12 human taphonomic research facilities globally, 10 of which are located across the USA and Canada (Figure 3.1) (Pecsi et al. 2020; Wescott 2018). The two remaining facilities are located in the Netherlands (Köppen-Geiger climate zone Cfb) and Australia (Köppen-Geiger zone Cfa) (Wescott 2018). The location of facilities across different geographic areas is advantageous, allowing researchers to compare and contrast observations across different environmental contexts (Wescott 2018). This can be extremely beneficial, for example, if trying to create a PMI estimation method generalizable across environments or specific to a given area.

The value of human subjects vs. animal analogs in decomposition research has been heavily debated. As this debate has been reviewed, at least in part, elsewhere (Belk et al. 2018a; Matuszewski et al. 2020), only the more salient points will be summarized here. In general, animal proxies are beneficial in controlled laboratory and field experiments where large sample sizes are necessary (Belk et al. 2018a). Intrinsic factors including health, diet, and living conditions are easily controlled in laboratory- or farm-reared animals such as mice (*Mus musculus*), rats (*Rattus rattus*), rabbits (*Oryctolagus cuniculus*), and pigs (*Sus scrofa*). In contrast, these same factors are often highly variable in humans and largely unknown depending on the availability of antemortem information. Furthermore, it is often challenging to establish a human taphonomic research facility. In addition to requiring substantial resources and community support, there are often numerous ethical and legal hurdles that must be circumvented (Oostra et al. 2020; Pecsi et al. 2020). Moreover, because the majority of human taphonomic research facilities are found in the eastern half of the USA, human subjects are inaccessible to the bulk of researchers globally. The scarcity of human-focused facilities means that there are fewer opportunities to test differential decomposition in humans related to factors such as climate (macro- and micro-) and geography. This is likely to change as the number of facilities continues to grow, propelled by research indicating that animal analogs are poor proxies for human decomposition (Connor et al. 2018; Dautartas et al. 2018; DeBruyn et al. 2021; Steadman et al. 2018). Therefore, it is often necessary to carefully consider the goals and objectives of a given research project and whether the advantages of using an animal analog outweigh the disadvantages. It is worth noting that decedents donated for human decomposition

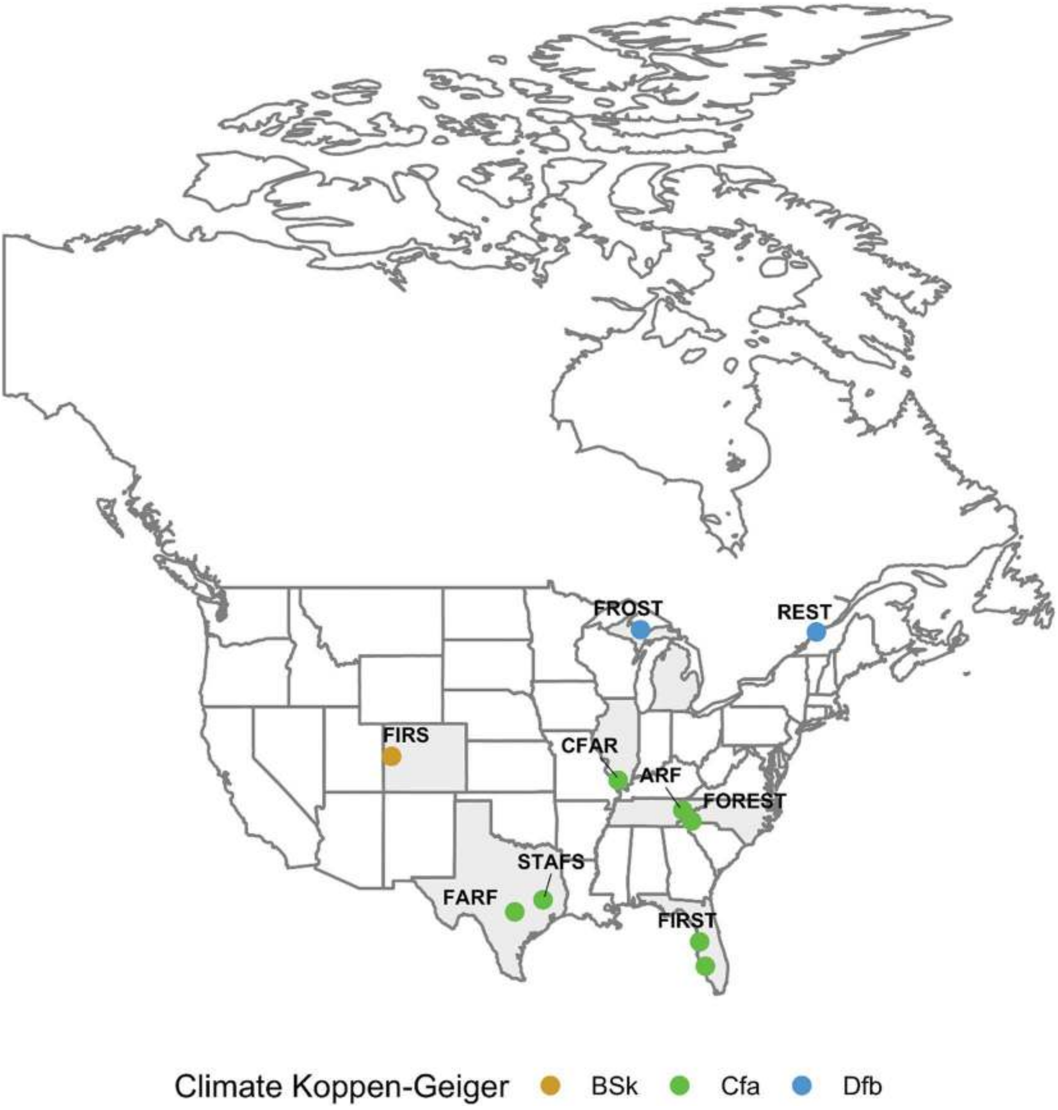

Figure 3.1 Human taphonomic research facilities in North America. US states with decomposition research facilities are highlighted in gray and approximate facility locations are color-coded using the updated Köppen-Geiger classification system (Cfa = warm temperature, fully humid, hot summer; BSk = arid steppe, cold arid; Dfb = snow, fully humid, warm summer). Acronyms refer to various facility names. If no acronym is associated with a facility, no acronym was provided here (Kottek et al. 2006).

research are generally non-representative of individuals recovered in a forensic context. For example, in Canada higher numbers of homicides were perpetrated on individuals up to 30 years old (Cockle and Bell 2019), while donated decedents are generally skewed toward older demographics. The mean age of decedents comprising the University of Tennessee's W. M. Bass Donated Collection, for example, is 62.6 years, which is similar among other research facilities (pers. obs.). Other notable concerns associated with research conducted at human taphonomic research facilities surround problems inherent to body donation programs. For example, there is often a delay between death and placement at human taphonomic research facilities due to the timing of donor discovery and shipping challenges (Simmons 2017). In addition, the degree to which storage practices arrest or alter decomposition is debatable (Micozzi 1986; Simmons 2017). Considering these problems, it may also be advantageous to collaborate directly with medical examiners on active cases when possible (Matuszewski et al. 2020).

Basics of Decomposition

Decomposition progresses in a continuous manner that is driven by two primary processes, autolysis and putrefaction (Janaway et al. 2009), and influenced by a number of intrinsic and extrinsic factors (Mann et al. 1990). To understand these processes better and the postmortem changes that result, researchers and practitioners often divide decomposition into a series of successional stages based on consistent gross postmortem changes and arthropod activity (e.g., Galloway et al. 1989; Marks et al. 2009; Payne 1965; Reed 1958; Rodriguez and Bass 1983; Vass et al. 1992). For example, Vass et al. (1992) argued that there are only two true stages of human decomposition, pre-skeletonization and post-skeletonization. While this may be true, research on postmortem decay generally focuses on the former, which encompasses and divides soft tissue decomposition into multiple stages. For a basic review of decomposition, the stages outlined by Galloway et al. (1989) and further modified by Megyesi et al. (2005) for more temperate climates (i.e., fresh, early decomposition, advanced decomposition, and skeletonization) will be used. These stages are similar to those outlined by other stage systems, but unlike other stage systems (Payne 1965; Rodriguez and Bass 1983), bloat and active decay are combined. The following caveat should be noted: while the postmortem physiochemical and biological changes outlined below often appear chronologically, in reality, certain changes could appear earlier, later, or never during decomposition.

Autolysis and Putrefaction

Decomposition begins within minutes of death. Cardiac arrest prevents blood and oxygen from circulating throughout the body (Gill-King 1997). Though normal cellular functions continue until oxygen is depleted, intercellular pH declines with circulatory system failure, and eventual anoxia disrupts ATP production and biosynthesis. Fermentative pathways, such as the conversion of pyruvate to lactic acid, try and fail to compensate for the decrease in ATP production brought on by the loss of cellular respiration, leading to a drop in cytoplasmic pH. As biosynthesis and cellular repair continue to falter, cellular and organellar membrane integrity is weakened (Gill-King 1997). This chain of events initiates autolysis, i.e., the postmortem breakdown of cellular material via enzymatic “self-digestion” (Forbes et al. 2017; Gill-King 1997; Swann et al. 2010). Due to a loss in membrane integrity, cell lysosomes release hydrolytic enzymes. Activated by the acidic cytoplasmic space, these enzymes continue to destroy organelle and cell membranes as well as other cellular structures and macromolecules, eventually dumping cellular content into intercellular spaces (Gill-King 1997). While autolysis begins in the fresh stage of decomposition, many of the notable macroscopic changes, to be discussed below, are not observed until early decomposition (Galloway et al. 1989; Megyesi et al. 2005). Differential rates of autolysis are generally due to differences in energy requirements; cells with greater metabolic activity (Gill-King

1997) and those with greater lysosome counts (Clark et al. 1997; Forbes et al. 2017) typically degrade first. This results in the gastrointestinal system being among the first tissue systems to degrade and those of the connective tissue and integument among the last (Gill-King 1997). In addition, a fresh carcass harbors a diverse community of host-associated microorganisms from the skin, gut, and mouth. With the shift to an anaerobic environment, unchecked symbiotic gut bacteria proliferate, decomposing the body internally through a process known as putrefaction (Carter et al. 2007; Forbes et al. 2017; Gill-King 1997; Swann et al. 2010). Though autolysis is the first degradative process to commence following death, autolytic and putrefactive processes occur simultaneously, making their effects difficult to disentangle (Forbes et al. 2017). Throughout putrefaction, large macromolecules (e.g., lipids, proteins, nucleic acids, and carbohydrates) are catabolized by bacterial fermentation, resulting in the production of organic acids (e.g., propionic, butyric, acetic, acetoacetic, and lactic acids) and gases (e.g., methane, carbon dioxide, ammonia, and hydrogen sulfide), which cause the abdomen and other regions of the body to bloat (Carter et al. 2007; Gill-King 1997; Swann et al. 2010). Alcohols are an additional byproduct of fermentation and include ethanol, methanol, propanol, and butanol (Forbes et al. 2017). Putrefaction has been associated with increased abundances in taxa from Lactobacillaceae, Bacteroidetes, and Lachnospiraceae (DeBruyn and Hauther 2017; Metcalf et al. 2013), with later proliferations of *Clostridium* (Burcham et al. 2019; DeBruyn and Hauther 2017).

Stages of Decomposition

Fresh

The *fresh stage* of decomposition is characterized by minimal macroscopic tissue changes. Though decomposition has begun, at this point, the consequences of autolysis are largely non-visible (Galloway et al. 1989), aside from potential clouding of the cornea (Tsokos 2005). While fly activity, including feeding and oviposition, often begin quickly after death (Carter et al. 2007), the fresh stage of decomposition is characterized by a lack of maggot activity (Galloway et al. 1989). However, visible patches of eggs, from flies such as blowflies and muscid flies, may be observed in the orifices (nose, mouth, ears, anus), eyes, and scrotum or vagina (Galloway et al. 1989; Rodriguez and Bass 1983), as well as on other moist and protected areas.

In addition, other early postmortem changes, independent of autolytic or putrefactive processes, may be visible, including the onset of pallor, or the gradual whitening of skin, and muscle relaxation, which results in the release of bowels (Clark et al. 1997). Moreover, if the eyes are open following death, drying of the corneal epithelium will leave a dark band of discoloration known as "tache noir" (Clark et al. 1997; Goff 2009; Tsokos 2005). Such changes are common in the first two hours after death. From one to four hours after death, and potentially earlier, the three mortises (livor mortis, rigor mortis, and algor mortis) can begin (Clark et al. 1997). Livor mortis, which commences approximately one-hour postmortem, is the gravitational pooling of blood. Livor mortis results from the failed circulatory system, without which, blood settles with gravity in those regions that are lowest (Goff 2009). Discrepancies in the timing of the fixation of livor mortis have been reported. For example, Goff (2009) reported the fixation of livor at 9–12 hours, while Tsokos (2005) reported the range of fixation at 18–24 hours postmortem. Color changes due to lividity are the only color changes observed in the fresh stage of decomposition (Galloway et al. 1989) (Figure 3.2). Rigor mortis involves the stiffening of the muscles as the ATP transport

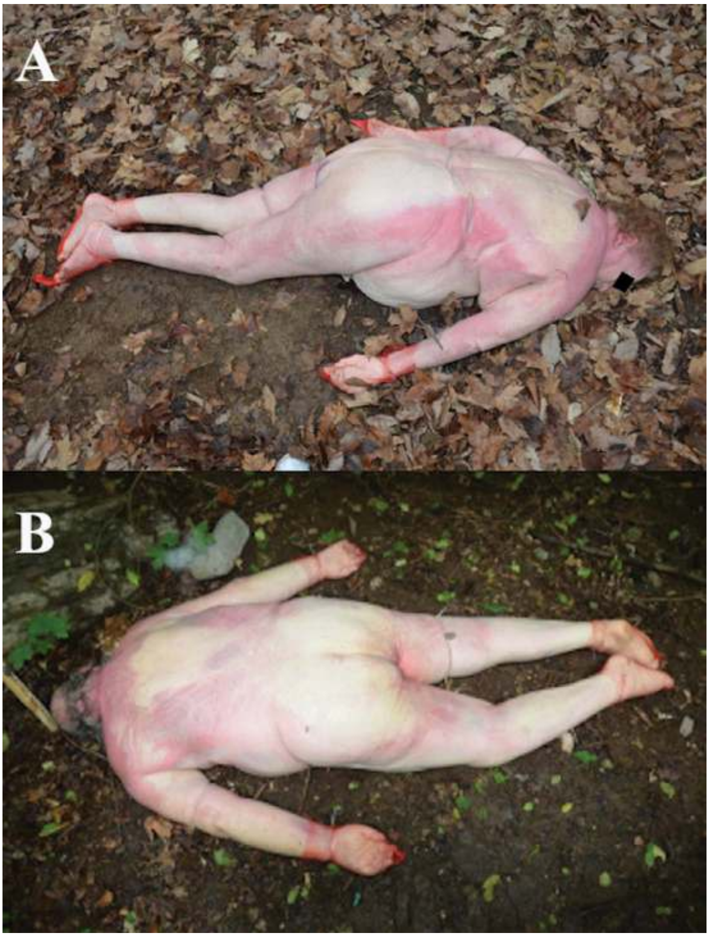

Figure 3.2 Examples of fresh decomposition (a and b). Visible reddish color changes are due to *livor mortis*. Individuals were placed at the Anthropology Research Facility, University of Tennessee, Knoxville following the fixation of *livor*. Contact blanching on the backs of a and b due to areas of compression and vessel obstruction are visible.

chains shut down and calcium is no longer pumped back into the sarcoplasmic reticulum to release bound actin-myosin complexes (Gill-King 1997). Rigor does not occur in all of the muscles at once but progresses unevenly, typically beginning in the face (Goff 2009); it generally persists until approximately 48 hours postmortem and can range between 24- and 84-hours postmortem (Gill-King 1997; Goff 2009). Variables including ambient temperature and antemortem activity level can impact the timing of rigor, with increased temperatures and high antemortem activity resulting in an earlier onset (Goff 2009). Algor mortis is the equilibration of postmortem body temperature with the surrounding environment; this usually occurs within 18 to 20 hours postmortem (Goff 2009). Algor is influenced by a number of variables including ambient conditions, body mass, body position, or clothing and other coverings (Madea 2016).

Early Decomposition (Active Decay)

Early decomposition may begin as early as 24 hours postmortem (Galloway et al. 1989) and is characterized by the effects of autolysis and putrefaction. This stage of decomposition

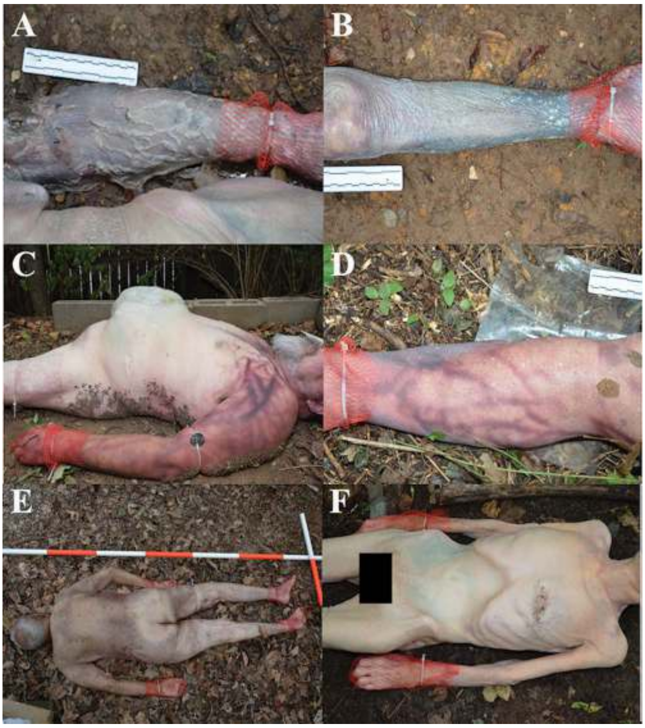

Figure 3.3 Early decomposition. (a) Skin slippage, (b) skin blistering and green/gray discoloration, (c) marbling on the left arm and green discoloration of the abdomen, (d) marbling, (e) dark red marbling and grayish discoloration; contact blanching has persisted into this stage, and (f) green discoloration of the abdomen.

begins with the effects of autolysis followed by discoloration from early putrefaction and postmortem drying and proceeds through a period of active decay, including bloat and post-bloat (Galloway et al. 1989; Megyesi et al. 2005). Visible signs of autolysis at this stage include skin slippage (Figure 3.3a), fluid-filled blisters (Figure 3.3b), and hair loss (Clark et al. 1997; Galloway et al. 1989; Shirley et al. 2011; Swann et al. 2010). In addition, the proliferation of bacteria and the breakdown of organic material by these bacteria (i.e., putrefaction) cause color changes, odors, and tissue distention or bloat (Carter et al. 2007; Gill-King 1997) that are characteristic of early decomposition. One of the most noticeable color changes involves a greenish-purplish hue, most prominent along the abdomen (Swann et al. 2010) (Figure 3.3c and f). This is the result of two simultaneous processes. The first involves the release of bile pigments via enzymatic action following cell lysis of pancreatic tissues (Gill-King 1997; Swann et al. 2010), while the second involves the conversion of hemoglobin, released from autolytic erythrocytes (Tsokos 2005), to sulfhemoglobin in the presence of hydrogen sulfide, a gas resulting from microbial catabolism (Gill-King 1997; Tsokos 2005). These processes also result in the phenomenon known as "marbling" (Gill-King 1997), so named due to the mottled or marbled appearance of superficial vessels (Figure 3.3c–e). Other color changes, including yellowish-brownish colors of the extremities, may be observed due to postmortem drying (Galloway et al. 1989; Wilson-Taylor and Dautartas 2017).

Color changes accompany bloating of the face, abdomen, and scrotum (in males) (Carter et al. 2007; Tsokos 2005) (Figure 3.4a and b). Pressure due to accumulating gases

Figure 3.4 Early decomposition: bloat and rupture. (a) and (b) Decedents with significant abdominal bloating and larval activity. In (b), a small CDI is also visible. (c) Decedent in post-bloat following rupture. There is extensive larval activity and a wide CDI.

eventually results in the purging of materials from the eyes, mouth, nose, and anus. Continued pressure paired with extensive insect activity and larval feeding produce tears or breaks in the skin causing the abdominal cavity to rupture, spilling further decomposition byproducts into the surrounding soil (Carter et al. 2007) (Figure 3.4c). At this point, anaerobic gut bacteria are replaced by aerobic bacteria such as Alphaproteobacteria (families Phyllobacteriaceae, Hyphomicrobiaceae, and Brucellaceae) and Gammaproteobacteria (family Enterobacteriaceae) (Metcalf et al. 2013). Purged fluids, containing high concentrations of nutrients from the decomposing cadaver, create an area of fertility surrounding the body, generally referred to as a *cadaver decomposition island* (CDI) (Carter et al. 2007). In response to the influx of available nutrients in the CDI, there is a measurable shift in soil microbial communities, in which more copiotrophic, or nutrient-loving, microbes are thought to dominate (Metcalf et al. 2013).

Advanced Decomposition

In multiple stage systems, *advanced decomposition* or *decay* coincides with larval migration (Carter et al. 2007; Payne 1965). In staying consistent with stages outlined by Galloway

Figure 3.5 Advanced decomposition. (a) and (b) Moist decomposition with initial skeletonization of the cranium. In (b), a wide CDI surrounding the decedent is also visible. The decedent had been autopsied. (c) and (d) Remains are deflated, wrinkled, and desiccated; larval activity is no longer visible. In (c), white fungal growth is visible on the neck of the decedent.

et al. (1989) and Megyesi et al. (2005), advanced decomposition begins toward the end of active decay, preceding larval migration. At its earliest manifestation, the body takes on a deflated, wrinkled appearance as continued and intense maggot and other insect activity result in extensive mass loss (Carter et al. 2007; Galloway et al. 1989; Wilson-Taylor and Dautartas 2017). At this time, decomposition appears moist and initial skeletal exposure is observed (Galloway et al. 1989; Megyesi et al. 2005) usually in regions of the body with the least amount of soft tissue and the greatest amount of insect activity, such as the cranium (Wilson-Taylor and Dautartas 2017) (Figure 3.5a and b). Advanced decomposition is also characterized by a rich CDI in the cadaver-associated soil that is high in carbon, nitrogen, and other nutrients (e.g., magnesium, calcium, phosphorus, and potassium) (Carter et al. 2007). In addition, the arthropod order Diptera (fly taxa) no longer dominates and is replaced largely by Coleoptera (beetle taxa) (Campobasso et al. 2001). By the end of advanced decomposition, mummification of remaining recalcitrant tissues is common (Galloway et al. 1989) (Figure 3.5c and d).

Skeletonization

Skeletonization is characterized by greater than 50% skeletal exposure of decomposing remains (Galloway et al. 1989; Megyesi et al. 2005; Swann et al. 2010) (Figure 3.6). Excluding the underlying soil (Barton et al. 2016; Cobaugh et al. 2015; Damann et al. 2012; Singh et al. 2018), skeletonization is often coupled with a reversion of the surrounding environment to its original state (Payne 1965).

Though skeletonization is often perceived as the terminus of decomposition, as alluded to by Vass et al. (1992), the duration of a "post-skeletonization" stage far surpasses that of soft tissue decomposition. Following soft tissue decomposition, bone continues to interact

Figure 3.6 Skeletonization. (a) and (b) skeletonized remains surrounded by liquefied fat and other tissue. The decedent in (b) underwent an autopsy. (c) Scattered, dry human remains, likely due to scavenging.

with the environment through a process known as diagenesis (Keenan 2016). The surrounding physical biogeochemical environment can either augment or inhibit chemical and/or microbial bone degradation (Collins et al. 2002; Kendall et al. 2018), which will eventually result in one of two possible outcomes, degradation or fossilization.

Adipocere Formation and Mummification

Adipocere formation and mummification are two preservative processes that can arise at any point during soft tissue decomposition. As atypical events during decomposition, preservation via adipocere formation or mummification can complicate medicolegal investigations, especially when estimating the postmortem interval. Adipocere, known as "grave wax", has been described as a soft, hard, greasy, or waxy white/gray material or saponified fat (Ubelaker and Zarenko 2011) (Figure 3.7a and b). It results from the hydrogenation of free fatty acids to saturated fats such as myristic, palmitic, and stearic acids (Forbes et al. 2004). Other components of adipocere include "unsaturated fatty acids, salts of fatty acids, and hydroxy- and oxo-fatty acids" (Forbes et al. 2005:24). The salts that accumulate from interactions with the surrounding environment influence the formation of adipocere, progressing from a hard "crumbly" texture with the addition of sodium to a soft "paste-like" texture with additions of potassium (Forbes et al. 2005; Gill-King 1997). In environments with high mineral contents, calcium or magnesium ions can replace sodium

Figure 3.7 Adipocere formation on the legs of (a) and (b).

and potassium, resulting in a hardened material (Forbes et al. 2005; Gill-King 1997). The minimal variables required for adipocere formation include “adipose tissue, moisture, bacteria, and anaerobic conditions” (Forbes et al. 2005:32). Though adipocere generally forms in wet environments, moisture produced from the decomposition process itself can be sufficient for its formation (Fiedler and Graw 2003), especially if the body is contained within a non-permeable enclosure (e.g., clothing, wrappings) (Byard et al. 2020; Clark et al. 1997). Reducing (or anaerobic) environments, such as water and burials, in particular are conducive to adipocere formation (Fiedler and Graw 2003; Forbes et al. 2005).

Mummification typically occurs in dry environments under extreme temperatures (either hot or cold) (Clark et al. 1997) but can also occur under a number of other environmental conditions. Unlike desiccation, or the loss of moisture in decomposing tissues, mummification occurs when moisture loss is complete and decomposition halts (Lennartz et al. 2020). When discussed in the context of forensic taphonomy, natural mummification is generally the focus, but the process may also be intentional, such as in funerary treatments (e.g., Egyptian mummies). Important factors related to mummification include temperature, humidity, precipitation (Lennartz et al. 2020), and scavenging (Jeong et al. 2016; Chapters 7, 9, 16, and 19).

Intrinsic and Extrinsic Factors Related to Decomposition

The biological and physicochemical changes associated with decomposition are influenced by a number of factors that can be divided into two categories: extrinsic and intrinsic (Wescott 2018). Extrinsic factors include abiotic (e.g., temperature, humidity, precipitation, oxygen availability, pH, solar radiation, coverings and clothing, body deposition, trauma, etc.) and biotic environmental variables (e.g., microbes, arthropods, and vertebrate scavengers). Intrinsic factors are related to the antemortem health, biology, and physiology of the decedent, and include some of the most difficult variables to test, especially using human subjects, due primarily to donor availability. Examples of intrinsic factors include body mass, sex, age, health, and the microbiome. Many of these factors are interrelated, likely acting together to increase or decrease the decomposition rate or influence the probability of different decomposition outcomes: liquefaction, desiccation, mummification, adipocere formation, or a combination of thereof. The following section provides an overview of select intrinsic and extrinsic factors frequently referenced in taphonomic research.

Extrinsic Factors (Abiotic and Biotic Environmental Factors)

The most important factor related to the rate of decomposition is temperature (Gill-King 1997; Mann et al. 1990; Vass et al. 1992). Chemical and biological activities are regulated by temperature, which can be explained in part by the kinetics of enzymatic reactions. As a general rule, the rate of enzymatic activity increases by a factor of two or three for every 10°C increase in temperature (Gill-King 1997), at least under some conditions, as differences in reaction activation energies and the fraction of molecules able to react play a role (Davidson and Janssens 2006). More recalcitrant substrates have higher activation energies and are therefore more temperature sensitive. Other factors such as enzymatic affinity and substrate concentration, which are easily impacted by the environment, also influence reaction rates. In addition, enzymes have temperature optima, above which they denature (Davidson and Janssens 2006). Enzymatic activity, reaction efficiency, and biological activity are inexorably linked. Both insect activity and microbial activity are regulated by temperature as well as a suite of other environmental factors. For example, warmer temperatures are associated with increased insect abundance (Campobasso et al. 2001; Payne 1965), biodiversity, and rates of insect development, while temperatures closer to 0°C result in larval death (Campobasso et al. 2001). Maggot masses can also generate heat, minimally 5°C above ambient temperatures (Simmons et al. 2010b), which may act as a buffer against declining ambient temperatures (Anderson et al. 2019). Similarly, higher temperatures have demonstrated increased rates of microbially mediated carrion decomposition (Carter et al. 2008).

To account for and normalize the impact of temperature on the rate of decomposition, researchers over the last few decades have incorporated units of available thermal energy such as Accumulated Degree Days (ADD) (e.g., Aitkenhead-Peterson et al. 2012; Ceciliason et al. 2018; Connor et al. 2019; Megyesi et al. 2005; Metcalf et al. 2013, 2016; Moffatt et al. 2016; Vass et al. 1992), Accumulated Degree Hours (ADH) (e.g., Benbow et al. 2013; De Jong et al. 2011), and Cumulative Degree Hours (CDH) (e.g., Hauther et al. 2015; Parmenter and MacMahon 2009; Vass et al. 2002) into their research. Thermal energy units have classically been used by forensic entomologists to track stages of development in insects (Anderson 2000). These units often include a parameter known as base temperature, below which biological processes cease (Megyesi et al. 2005). For example, ADD are calculated by summing the average daily temperatures above the base temperature over a given time period (i.e., the decomposition time frame) (Megyesi et al. 2005). Similarly, ADH are calculated by summing average hourly temperatures minus the base/threshold temperature (Weatherbee et al. 2017). CDH are calculated by assessing temperature on a 12-hour scale; the average temperature above the base temperature for each 12-hour period over the duration of decomposition are summed (Vass et al. 2002). CDH and ADD, in particular, are useful for increasing the resolution of a PMI estimate.

Insect activity is the second-most important rate-limiting factor after temperature (Mann et al. 1990; Simmons et al. 2010a,b). While over 500 species of arthropods have been observed in association with carrion decomposition, the majority of species can be assigned to four taxonomic orders (Diptera, Coleoptera, Hymenoptera, and Acari) (Payne 1965). Of those, Diptera and Coleoptera dominate the decomposition process, with Diptera responsible for the majority of soft tissue decomposition (Campobasso et al. 2001). During the decomposition of pig carcasses in summer, the presence of insects accounted for an approximate 60% reduction in carcass mass over five days of decomposition compared with insect-excluded remains (Payne 1965). Moreover, in an experiment using rabbits assigned to four treatment groups (i.e., buried with insects, surface with insects, buried without insects, and surface without insects), Simmons et al. (2010b) showed that insect presence was the primary determinant of the decomposition rate when accounting for temperature. Pechal et al. (2014a) observed a similar relationship between insect activity and the decomposition rate. Carcasses with delayed necrophagous insect exposure remained in bloat over the first five days of decomposition, while insect-exposed remains progressed well into active decay. Moreover, Payne (1965) noted an alternative decomposition trajectory and created a separate stage system for insect-excluded remains, which were more likely to experience desiccation and mummification.

Insect activity and microbial activity are additionally influenced by the presence of water via humidity, precipitation, soil moisture, tissue moisture, etc. Flies will avoid desiccated remains during oviposition (Campobasso et al. 2001), and tarsal (lower leg) contact with water has been associated with increased oviposition among certain blowfly species (Browne 1962). This behavior is likely related to the susceptibility of eggs and larvae to desiccation. Furthermore, researchers have observed a negative relationship between life history traits (e.g., development rate, duration of larval stage, size of larvae, and dry mass of emerging adults) and reduced food moisture levels in the forensically relevant secondary screwworm (Diptera: Calliphoridae) (Bauer et al. 2020). Moisture and water content also constrain microbial activity by mediating the diffusion of oxygen, nutrients, and wastes within a given environment and allowing or impeding microbial motility (Carter et al. 2010). In gravesoil, for example, Carter et al. (2010) demonstrated that microbial efficiency was related to optimal water content in soils—neither too high nor too low—which was influenced by soil texture. Moisture is additionally necessary for the diffusion of extracellular enzymes and their interaction with a particular substrate (Davidson and Janssens 2006).

The role of microbes in decomposition has become an increasingly popular topic over the last decade, coinciding with advancements in nucleic acid sequencing technologies. As discussed above, enteric bacteria are extremely important for putrefactive processes in early decomposition, and there is evidence that some gut bacteria persist in the surrounding gravesoil even after soft tissue decomposition ends (Cobaugh et al. 2015; Keenan et al.

2018). Moreover, research has shown that microbes originating from the soil environment play a substantial role in carrion decomposition, increasing the rate of decomposition by a factor of two or three (Lauber et al. 2014). Other potential microbial sources include necrophagous insects (Metcalf et al. 2016), other invertebrate scavengers, vertebrate scavengers, and transient sources (e.g., water). Evidence suggests that not only do insects play a role in the dispersal of bacteria, but they also rely on bacteria to locate carrion sources (Ma et al. 2012; Tomberlin et al. 2012). Bacterially produced compounds (e.g., putrescine, NaOH, KOH, NH_3, phenol, and lactic acid) used for quorum-sensing, a microbial system in which microbial cell density influences gene expression regulation, also attract blowfly species (Ma et al. 2012; Jordan et al. 2016).

There are a number of additional factors that affect the rate of decomposition including but not limited to the presence of clothing, other coverings, trauma, pH, funerary practices (e.g., embalming), burial/burial depth, scavenging, seasonality (Mann et al. 1990), geography, and other deposition environments (e.g., water, indoors, outdoors without soil contact, etc.) (Wescott 2018). Many of these factors are interrelated. For example, given that temperature, humidity, and precipitation can influence cadaver decomposition, it may come as no surprise that the decomposition rate is influenced by seasonality. Seasonal differences also affect microbial (Carter et al. 2015; Randall 2021) and necrophagous insect communities (Benbow et al. 2013), which, in turn, impact decomposition. Clothing has been shown to affect decomposition in pig carcasses by prolonging the duration of moist decomposition by retaining moisture and deterring desiccation (Kelly et al. 2009; Voss et al. 2011). Though trauma has been associated with increased rates in decomposition, influenced by greater oviposition and larval activity at wound locations (Mann et al. 1990), recent research suggests that trauma does not alter the rate of decomposition (Bates and Wescott 2016; Cross and Simmons 2010) but may alter the overall pattern (Smith 2014). Conversely, others have shown a correlation between delayed decomposition and trauma with moderate-to-high blood loss (c.f., Cockle and Bell 2019). Vertebrate scavengers can consume large amounts of carrion flesh, but their presence is affected by temperature, insect activity, habitat, and microbial activity (DeVault et al. 2004). For example, it is likely that the production of low levels of volatile organic compounds (VOCs) attracts scavengers to carcass localities, while increased microbial and insect activity, high concentrations of VOCs, and reduced resource quality discourage scavenging (DeVault et al. 2003). Examples of vertebrate scavenging of soft tissue can be found in Figure 3.8.

Figure 3.8 Examples of scavenging due to raccoons (*Procyon lotor*) on decedents placed at the Anthropology Research Facility, University of Tennessee, Knoxville.

Burials, as opposed to surface decomposition, discourage access by vertebrate scavengers and insects and moderate temperature changes with depth, thus drastically slowing the decomposition rate (Bachmann and Simmons 2010; Rodriguez 1997; Rodriguez and Bass 1985; Troutman et al. 2014). Burial conditions including depth, soil texture, soil composition, pH, site hydrology, soil biogeochemistry/ecology, and other edaphic variables influence the rate and trajectory of decomposition (Troutman et al. 2014). Reducing conditions and anoxia promote decay by less efficient microbial decomposers (Carter et al. 2007) and may stimulate preservation through adipocere formation (Fiedler and Graw 2003). Soil pH can also limit microbial activity; more acidic pHs are associated with greater fungal activity, whereas bacteria are more active at neutral or slightly alkaline pHs (Forbes and Carter 2016).

Decomposition rates and patterns are also affected by the location in which the remains decompose. With smaller fluctuations in temperature and reduced access to insects and scavengers, bodies that decompose indoors are more likely to experience delayed colonization by insects, have a different insect diversity, and are more likely to experience a prolonged period of desiccation (Anderson 2011; Ceciliason et al. 2018; Goff 1991). Ritchie (2005) noted that the stable temperature allowed the insects to remain present on the body for a longer period of time and an extended period of bloat, particularly in the winter when colder temperatures can limit bacterial activity.

Intrinsic Factors

The effect of cadaver mass or body size on various aspects of decomposition has been the focus of several studies (Fancher et al. 2017; Matuszewski et al. 2014; Parmenter and MacMahon 2009; Simmons et al. 2010a; Spicka et al. 2011; Sutherland et al. 2013; Vass et al. 1992; Weiss et al. 2016). Cadaver mass/size has been shown to affect the concentrations of volatile fatty acids (VFAs) (Vass et al. 1992) and other parameters of gravesoil chemistry in human CDIs (Fancher et al. 2017). Increased mass results in larger concentrations of various chemical parameters, which can impact PMI estimates (Fancher et al. 2017; Vass et al. 1992). Carcass mass showed similar results when assessing ninhydrin reactive nitrogen (NRN) released in gravesoil throughout the decomposition of swine carcasses (Spicka et al. 2011). Spicka et al. (2011) additionally examined the difference between neonates and juvenile/adult pigs in rate and concentration of released NRN into the surrounding soil. They found that neonates decomposed significantly faster than non-neonates. However, while gravesoils associated with neonates demonstrated greater concentrations of NRN per unit carcass, the rate of NRN released from neonates was much slower than larger carcasses (Spicka et al. 2011). Simmons et al. (2010a) and Matuszewski et al. (2014) similarly observed a faster rate of decomposition for smaller pig carcasses, but in the case of Simmons et al. (2010a), carcass mass only influenced the decomposition rate when insects were present.

As many of these studies were conducted on pigs, it is unclear how these observations relate to humans, and studies incorporating humans seem to show alternative results. For example, Mann et al. (1990) observed minimal differences in decomposition due to cadaver size, and on two occasions noted that larger cadavers decayed more rapidly than smaller cadavers. Using 12 cadavers, Roberts et al. (2017) observed no significant difference in the decomposition rate of human subjects from three mass classes (<105 kg, 105–120 kg, and >120 kg). The authors did note greater degrees of liquefaction and increased presence of adipocere in larger individuals, as well as wider CDIs in those same individuals

(Roberts et al. 2017). Interestingly, Parmenter and MacMahon (2009) observed relatively few significant differences in carcass mass loss between 11 vertebrate species of varied sizes (not including humans and pigs) in the absence of scavenging. Larger carcasses, which supported larger insect populations, decomposed at rates similar to smaller carcasses. Conflicting reports also exist concerning the relationship between carcass mass and postmortem gravesoil microbial communities. When comparing microbial community structure between pig carcasses with different masses, Weiss et al. (2016) saw no significant differences in microbial communities. In contrast, Singh et al. (2018) observed a significant correlation between relative abundances of Gammaproteobacteria and initial cadaver mass. When considering overall microbial community structure by cadaver mass, however, there was no significant relationship (Singh et al. 2018).

There are few studies on the effects of variables such as sex and age on soft tissue decomposition. Sex seems to have no effect on the rate or pattern of soft tissue decomposition (Forbes et al. 2019; Mann et al. 1990), while the effects of age are more difficult to decipher. Representative demographics at human decomposition research facilities are skewed toward the old, and most research on infant or juvenile remains has been conducted on pigs. Fetal pig remains decompose significantly faster than juvenile (Ross and Hale 2018) or adult remains (Spicka et al. 2011). Such results are attributed to differences in carcass mass/size.

The human microbiome is another potential source influencing individual variability in the pattern and rate of decomposition. Though human microbiome research on the living has shown similarities in microbial community composition within different body habitats (i.e., gut, oral, skin, or vagina), differences by individual persist and are prominent (HMP Consortium 2012). This uniqueness among individuals has been the subject of forensic research focused on human identification (Fierer et al. 2010; Lax et al. 2015). Postmortem microbiome research has also centered on PMI estimation. Despite any differences that may exist in initial antemortem microbiomes, the succession of decomposer microbes appears to be consistent and reproducible across time (Metcalf et al. 2016), at least beyond 48 hours postmortem (Pechal et al. 2018). It is currently unknown how factors that affect human health and the microbiome in life (e.g., aging, antibiotic use, or other medicinal or recreational drug use) subsequently affect the necrobiome and thus the progression of decomposition in death. For example, a link between certain drugs taken antemortem and postmortem insect development has been demonstrated (Bourel et al. 1999). As more research is conducted, it will be interesting to see how previously ignored antemortem factors, largely due to a lack of body donor information, relate to postmortem inter-kingdom dynamics such as microbial, invertebrate, and vertebrate scavenging.

Estimating the Postmortem Interval

Due to the factors discussed above, one of the most difficult yet pertinent questions to answer in a medicolegal investigation, in the absence of sufficient investigational evidence, is the time since death or postmortem interval (PMI). As decomposition progresses, the PMI becomes more difficult to predict. While this is due in large part to the variability of the decomposition rate and associated postmortem changes, as argued by Wescott (2018), challenges in experimental design and implementation in related research are likely contributing factors. In general, there has been a lack of methods standardization, a lack of creativity in statistical modeling, a failure to incorporate human subjects, and a failure to move beyond descriptive research or research pertinent to a specific environment (Wescott 2018). The following section will review some of the most widely used PMI estimation methods in the context of forensic anthropology, especially those focused on postmortem macroscopic changes. The focus will then shift to a review of trending biomolecular and interdisciplinary methods. Methods associated with initial PMI estimation and PMI estimation via entomological evidence will only briefly be reviewed.

Initial PMI Estimation

Initial PMI estimation methods, within the first 24–48 hours, are generally more accurate than methods associated with longer PMIs. Typical methods used for early PMI estimation include an assessment of the "three mortises" and an examination of supravital reactions. The supravital reactions most pertinent to the PMI are the "mechanical and electrical excitability of muscle and pharmacologically induced excitability of the iris" (Madea 2016:454). Mechanical excitability of muscle (i.e., biceps brachii) is observable in stages with corresponding prediction intervals up to ~24 hours after death, while electrical excitability of the orbicularis oculi muscle provides a range of confidence intervals up to ~22 hours after death. Excitability of the iris can be induced by a number of drugs and may be observed up to ~46 hours after death (Madea 2016). (For approximate time ranges for rigor, algor, and livor mortis, see above.) Though the nomogram method to measure postmortem body cooling (i.e., algor mortis) has been cited as the "gold standard" of early PMI estimation methods (Madea 2016; Tsokos 2005), early PMIs can be more precisely and accurately estimated using a combination of methods (Madea 2016).

Arthropod Succession

It has been well established that the colonization of insects on decomposing carrion is successional (Campobasso et al. 2001; Payne 1965; Rodriguez and Bass 1983). Observed patterns of insect colonization and insect developmental timings have been exploited by forensic entomologists to estimate PMI. While such estimations are generally useful fairly early in the PMI (~2 weeks) (Metcalf 2019), entomological evidence can be used across longer time intervals (Wells and Lamotte 2010). However, like many methods used to estimate PMI, methods based on entomological evidence have a number of limitations. For example, developmental timings or successional patterns are based on laboratory or fieldwork conducted under specific conditions that do not always translate well to a given death scene (Wells and Lamotte 2010). Moreover, while there are a number of factors, both biotic and abiotic, that influence insect succession and contribute to uncertainty (Michaud 2012), there is also a degree of random variation even under seemingly similar conditions (Wells and Lamotte 2010).

Macroscopic Tissue Changes and Universal Models

Estimating the time since death via the degree of soft tissue change throughout decomposition has generally been a qualitative feat, resulting in wide PMI estimates based on anthropological expertise. The use of thermal units (i.e., ADD, ADH, CDH) as a predictive variable has allowed researchers to directly control for temperature, the foremost rate-limiting variable in decomposition and methods of PMI estimation, thus allowing previously qualitative methods to become more quantitative. The first use of ADD to estimate PMI outside of entomology is attributed to Vass et al. (1992), but the introduction of the total body score (TBS) and its relationship to ADD by Megyesi et al. (2005) was arguably equally transformative for the field of forensic anthropology. Megyesi et al. (2005) developed a composite scoring system (i.e., TBS) to quantify soft tissue decomposition across three regions of the body (head and neck, torso, and appendages). Point values were assigned to gross changes generally observed across the four broad stages of decomposition outlined herein (fresh, early decomposition, advanced decomposition, and skeletonization), so that early postmortem observations were assigned less points, while later observations were assigned more points. Values from each of the three scored regions were then summed to arrive at a single TBS. In this way, the TBS served as an indicator of the degree of soft tissue decomposition over time. Using retrospective data (e.g., photographic evidence from forensic case reports and historical temperature data), the authors demonstrated a relationship between log transformed ADD and TBS squared ($r^2 = 0.84$), indicating that combined time and temperature explain a large degree of variation in soft tissue decomposition assessed via TBS. The authors also provided an equation to predict a point estimate of ADD from TBS with an upper and lower 95% confidence interval; this equation can be used by investigators to back-calculate PMI from ADD to days using freely available temperature data (Table 3.1) (Megyesi et al. 2005). Historic temperature data are important for the success of this method. While temperature data may not be available for an exact location, data are available from numerous weather stations across the USA via the National Oceanic and Atmospheric Administration (NOAA 2021).

While the method of Megyesi et al. (2005) has exhibited high inter-observer reliability (Dabbs et al. 2016; Wescott et al. 2018), it has not shown consistent success across different environments neither when using the formula directly on human remains (Suckling et al. 2016; Wescott et al. 2018) nor when using TBS/ADD to construct a regionally specific formula using pigs (Myburgh et al. 2013). In addition, some researchers have pointed out flaws in the Megyesi et al. (2005) method, especially regarding their statistical approach. Switching response and predictor variables invalidated the linear regression model, resulting in an incorrect slope, while rounding the slope incorrectly reduced significant figures and inflated confidence intervals (Moffatt et al. 2016). On this basis, Moffatt et al. (2016) modified the original method of Megyesi et al. (2005) by incorporating a more appropriate statistical model (i.e., inverse prediction) and by modifying the original scoring method to instead start from zero. The authors generated their new model using a subset of the data from Megyesi et al. (2005), eliminating subjects with PMIs generated from entomological data, indoor subjects, and subjects with ADD greater than 3000 to simplify the model and reduce unnecessary variation. With the reduced data set and alternative formula, the method formulated by Moffatt et al. (2016) resulted in an r^2 value of 0.91 and reduced confidence intervals. However, because their model was constructed on a reduced data set, total body scores greater than 25 were not included, which would make this model inappropriate for TBSs greater than 25 (Table 3.1).

Forbes et al. (2019) compared actual vs. predicted ADD resulting from the model proposed by Megyesi et al. (2005) and the revised model by Moffatt et al. (2016) using pig remains in Cape Town, South Africa. They found that both methods failed to predict ADD accurately during winter but showed moderate success in summer. Though neither method appeared to outperform the other significantly, the Megyesi et al. (2005) method

Table 3.1 A Summary of Methods and Results Produced by Megyesi et al. (2005) vs. Moffatt et al. (2016)

	Decomposition Scoring Method	Model	Data Transformation	Equation	R^2	TBS Modifications
Megyesi et al. (2005)	TBS	Linear regression	Log10ADD, TBS2	ADD = 10(0.002*TBS*TBS+1.81) ± 388.16	0.84	Original method; TBS 3–35
Moffatt et al. (2016)	TBSsurf	Inverse prediction	Log10ADD, TBS1.6	TBSsurf = (125* log10ADD −212)0.625	0.91	TBSsurf 0–32; TBSsurf > 25 not included in the model

showed greater inaccuracy during early decomposition, while the Moffatt et al. (2016) method showed greater inaccuracy as decomposition progressed. Tested data, however, were limited to only four TBSs (12, 14, 18, and 22) (Forbes et al. 2019).

While the Megyesi et al. (2005) scoring method (TBS) is commonly applied to decomposition research (e.g., Ceciliason et al. 2018; Simmons et al. 2010a; Smith 2014; Steadman et al. 2018; Sutherland et al. 2013) and is used frequently at a number of human decomposition research facilities (Dabbs et al. 2016), other scoring methods have also been developed. Examples include the Total Decomposition Score (TDS) (Gelderman et al. 2018) and the Degree of Decomposition Index (DDI) (Fitzgerald and Oxenham 2009). TDS is similar to TBS, but TDS does not assign as much weight to the order of decomposition events. Rather, several postmortem changes associated with a given decomposition stage are assigned the same point value (Gelderman et al. 2018). The DDI method was developed using pig remains (Fitzgerald and Oxenham 2009). In this scoring system, a value between 0 and 5, each corresponding to a decomposition stage from Galloway et al. (1989), are assigned for each of eight body regions. The scores are then averaged, resulting in the DDI. However, it is unclear how this method would translate to human remains due to differences in body proportions. Others have also developed regionally specific scoring systems. For example, Connor et al. (2019) developed a scoring system (i.e., Total Body Desiccation Score [TBDS]) using a large sample size of human cadavers (n = 40) to model desiccation better in a high altitude/arid environment. Though TBDS showed similar model performance to TBS during early decomposition, when the authors focused on late decomposition (TBS > 20 and TBDS > 50), TBDS outperformed TBS (Connor et al. 2019).

In contrast to these scoring systems, the degree of decomposition has also been measured via an assessment of the percentage of mass/weight loss over time. Adlam and Simmons (2007) demonstrated a strong correlation between percent weight loss and a modified version of TBS using rabbit carcasses. In addition, a number of researchers have used the percentage of mass loss or other measure of carcass mass loss over time to quantify the rate of decomposition (e.g., Carter et al. 2008; Parmenter and MacMahon 2009; Payne 1965; Spicka et al. 2011). A related metric, the percentage of soft tissue decomposition, has been used to develop a "universal" PMI estimation model for human remains. Vass (2011) developed two formulae to predict PMI in either an aerobic (surface) or anaerobic (burial) environment by observing and correlating the percentage of soft tissue decomposition that occurred with time and other decomposition factors (Table 3.2). These formulae were developed to provide investigators with a simple method to estimate PMI, thereby facilitating their investigations while awaiting more complicated laboratory-based PMI

Table 3.2 **Vass (2011) "Universal" PMI Estimation Formulae**

Method	Equation
PMIaerobic	$= \dfrac{1285 \times \left(\dfrac{\text{Decomposition}}{100}\right)}{0.0103 \times \text{Temperature} \times \text{Humidity}}$
PMIanaerobic	$= \dfrac{1285 \times \left(\dfrac{\text{Decomposition}}{100}\right) \times 4.6 \times \text{Adipocere}}{0.0103 \times \text{Temperature} \times \text{Soil moisture}}$

estimates. The formulae incorporate several environmental factors such as temperature, moisture, and oxygen availability. For example, in PMIaerobic, 1285 represents the ADD at which soft tissue decomposition terminates as indicated by volatile fatty acid liberation. The factor "decomposition/100" is a subjective visual assessment of the percentage of decomposition that has occurred. The constant 0.0103 accounts for the effect of moisture on the decomposition rate. Temperature and humidity are single values (potential averages), ideally representative of the discovery site. The burial formula additionally considers the slower rate of decomposition due to less oxygen (constant 4.6) and incorporates a multiplier representative of the percentage of adipocere formation. Soil moisture, as a percentage, is also included. While Vass (2011) provided a clear description of the formula parameters and how to use his method, information on the data used to construct these models was not provided. Moreover, Vass (2011:39) stated that his aerobic decomposition formula had been applied "to many cases worldwide with remarkable success" but only supplied a few examples.

Research validating these formulae has shown mixed results (Cockle and Bell 2015; Maile et al. 2017; Marhoff-Beard et al. 2018). PMIaerobic has shown moderate success (accurate in 79% of 19 cases; 100% in Nebraska and 60% in Hawaii) when applied to indoor death scenes (Maile et al. 2017). It is worth noting that due to the difficulties of estimating the percentage of soft tissue decomposition, Maile et al. (2017) used a range of values for percent mass loss, which were based on classic decomposition stages and deviated from the ranges provided by Vass (2011). When applied to pig remains in New South Wales, Australia, PMIaerobic only slightly outperformed the formula of Megyesi et al. (2005), with an accuracy of 31% compared to 21%, respectively (Marhoff-Beard et al. 2018). Model performance drastically increased when testing the formula on five human decedents; predicted PMIs for four out of five individuals were within 1–2 weeks of known PMIs. In contrast, using data from 42 outdoor surface cases in Canada, Cockle and Bell (2015) found that PMIaerobic significantly overestimated PMI in warm environments and underestimated PMIs in cold environments. In addition, when comparing the rate of decomposition between 22 burial cases and 96 surface cases, they discovered that the 4.6 rate constant proposed by Vass (2011) and included in PMIanaerobic was invalid; the rate of decomposition was highly variable between surface and buried remains and was also unrelated to burial depth (Cockle and Bell 2015).

Due to inaccuracies across seasons and environments in these "universal" methods, there has been a general call to develop regional-centric PMI estimation models to incorporate more fully unique geographical, climatic, or other variables (Cockle and Bell 2015;

Wescott 2018). Decomposition is a highly variable process influenced by a number of factors that can impact PMI estimation models. The quest for a universal model continues and may be found within the more arduous biomolecular methods (see below). Regardless, the ability to calculate an accurate PMI using gross soft tissue changes, in particular, continues to be an important goal in forensic taphonomy, whether universal or regional. Unlike biomolecular methods, methods based on gross tissue changes generally require less time, less technological expertise, and less capital (labor, consumables, technology/machinery, etc.).

Biomolecular Methods

In an attempt to estimate PMI more accurately, researchers have turned to biomolecular approaches. This has included but is not limited to lipidomics, proteomics, and the characterization of volatile organic compounds and volatile fatty acids. In addition, microbial methods for estimating PMI have become increasingly popular. These methods and their history and merit for estimating the PMI are discussed below.

Microbiome

The important role of microbes in the decomposition process has prompted researchers to investigate whether they can be used to estimate the PMI more accurately than traditional methods or complement them to improve overall confidence/estimates. Many studies (Belk et al. 2018b; Damann et al. 2015; DeBruyn and Hauther 2017; Finley et al. 2016; Hauther et al. 2015; Javan et al. 2016; Metcalf et al. 2013, 2016; Pechal et al. 2014b, 2018) have indicated that the microbial communities that facilitate decomposition change in a repeatable, predictable manner, allowing researchers to create a so-called "microbial stopwatch of death". Metcalf et al. (2013) characterized the microbiome of decomposing mice for the first 48 days of decomposition. This was achieved using high-throughput sequencing of partial 16S ribosomal RNA (rRNA) and partial 18S rRNA genes, which is a quick and relatively inexpensive way to identify members of the bacterial/archaeal and microbial eukaryotic communities, respectively. To estimate PMI, a Random Forests model was used to regress known PMI directly on the taxon relative abundances, giving an error of ± 3 days over the 48-day experiment. While other studies had previously modeled indicator taxa in an attempt to predict the stage of decomposition (Pechal et al. 2014b), this was the first attempt at mathematically modeling an entire microbial community to estimate PMI, demonstrating the potential for this technique to be developed into a forensic tool. To confirm whether microbial succession could be used to estimate PMI, Metcalf et al. (2016) and others (discussed below) have extended these methods to human models. Researchers discovered a suite of microbes within the human decomposer community that emerge at predictable times (Metcalf et al. 2016), and these data can be used to estimate PMI with an error of ± 5 to 6 days over a decomposition period ranging from 48 to 142 days (Belk et al. 2018a).

While these and other studies (Finley et al. 2016; Pechal et al. 2014b) were performed on sample types including skin and gravesoil, other studies have investigated decomposer microbial communities of the gut (DeBruyn and Hauther 2017; Hauther et al. 2015), eyes, nose, ears, mouth, rectum (Pechal et al. 2018), brain, heart, liver, spleen, blood (Javan et al. 2016), and bone (Damann et al. 2015) in an effort to determine what sample type best predicts PMI. Microbial methods for estimating PMI are showing promise, with a vast amount of work remaining to develop these into practical forensic tools. Future research includes sampling more frequently to improve model accuracy, determining which type of mathematical model is best suited for using microbial abundance information to estimate PMI, and collaborating with a variety of anthropological facilities in different climates to create a more inclusive and generalizable microbial stopwatch of death. Only after these knowledge gaps are addressed (Metcalf 2019) and the integration of microbiome science in forensics (Clarke et al. 2017) is achieved will these methods be useful for estimating PMI in death investigations.

Lipidomics

Another promising PMI biomarker gaining attention in the forensic sciences includes lipids. Lipids are crucial components of cellular membranes, and there are tens to hundreds of thousands of lipid compounds that constantly change under different physiological and environmental conditions (Yang and Han 2016). Because decomposition is a highly dynamic environment and bone lipids are known to survive extreme environmental conditions (Collins et al. 2002), researchers are investigating whether the degradation of lipids (primarily those associated with cellular membrane structure) could be used to estimate PMI. With advances in mass spectrometry over the last two decades, the field of “lipidomics” has developed, allowing the study of cellular lipids on a large scale. The first application of lipidomics to identify lipid biomarkers of PMI was by Wood (2012), where sections of the anterior quadriceps were collected from human skeletal muscle at 1, 9, and 24 days postmortem. “Shotgun lipidomics” using high-resolution mass spectrometry analysis revealed several lipids that decreased with advancing decomposition, including sterol sulfates, very-long-chain fatty acids, and multiple lipids that form major structural components of cell membranes, including phosphatidylglycerol. In addition, there was an accumulation of short-chain fatty acids that typically act as energy sources for the decomposer microbiome. Langley et al. (2019) used a similar approach to detect biomarkers of postmortem degradation, but instead sampled human skeletal muscle tissue from the vastus lateralis daily until 2000 ADD were reached. The most commonly found lipids were phosphatidylglycerol and phosphatidylethanolamine, both of which are cellular membrane structural components. Langley et al. (2019) used phosphatidylglycerol concentration to generate a simple linear regression model that was able to predict PMIs of test subjects with a 100% success rate, with all predictions falling within the 95% confidence interval. While this study did not translate these results to PMI error in terms of days, the success rate at ADDs as high as 2000 is promising, considering the difficulty of estimating late-term PMI (see “Using Skeletal Remains for Estimating Late PMI” section, below). To develop this technique further, additional shotgun lipidomics studies are required to investigate the predictive potential of other skeletal muscles and the utility of this method in later decomposition stages or extended PMIs. Moreover, researchers should test how robust the postmortem lipidome is to climatic and/or environmental differences. Regardless, the human decomposer lipidome shows potential as a suitable method for providing quantitative, objective estimates of PMI.

Proteomics

Similar to the postmortem lipidome and microbiome, the postmortem proteome has become an important area of research in the quest to discover reliable markers of PMI. While a variety of methods have been used for protein/proteomics analysis, currently the most commonly used methods for characterizing the proteome of a cell, tissue, or organism of interest have been liquid chromatography with tandem mass spectrometry (LC-MS/MS) and matrix-assisted laser desorption/ionization-time of flight (MALDI-TOF) (Aslam et al. 2017). Hundreds of proteins are known to survive extreme decomposition environments with a slow rate of decay over time (Buckley and Wadsworth 2014; Cappellini et al. 2012; Procopio et al. 2018b; Sawafuji et al. 2017), which has prompted forensic scientists to investigate the predictive potential of protein degradation to estimate PMI. One of the earlier protein studies used an enzyme-linked immunosorbent assay to discover that HMGB1, a nonhistone DNA-binding protein that is released by eukaryotic cells upon necrosis, increases in serum blood levels for up to seven days postmortem in rats (Kikuchi et al. 2010). Excluding this experiment, most proteomics analyses in a forensic context have been performed on bone. Initial experiments on bone were conducted in an archaeological context. Such experiments focused on the identification of proteins that survived in archaeological bone (Buckley and Wadsworth 2014; Cappellini et al. 2012; Schweitzer et al. 2002) and explored the reproducibility of bone proteomics to inform future experimental designs (Procopio et al. 2017). Procopio et al. (2018b) investigated the applicability of bone proteomic analysis to identify biomarkers of PMI in the tibiae of four buried pig carcasses at 1, 2, 4, 6, and 12 months postmortem. Proteomics performed by LC-MS/MS showed that the most significant proteomic changes occurred within four months postmortem, after which proteins began to decay more slowly. Proteins that quickly decayed (between one and four months postmortem) included some plasma proteins, like hemoglobin A and B, transferrin, and lactoferrin, and the metabolic protein triosephosphate isomerase. Moreover, some muscle proteins, myosins type 2 and 6, beta-enolase, creatine kinase M-type, and haptoglobin, showed decreasing trends over PMI. In contrast, there was an increase in asparagine deamidations in biglycan with increasing PMI (Procopio et al. 2018b). Choi et al. (2019) conducted a similar study investigating the utility of proteomic analysis for estimating PMI using rat and mouse skeletal muscle proteomes at 24, 48, 72, and 96 hours postmortem. Several hundreds of rat and mouse proteins were identified (579 and 896, respectively). Of these, they found that the proteins eEF1A2 (a translation factor) and GAPDH (a widely used housekeeping protein) showed a consistent postmortem degradation rate in both animal models (Choi et al. 2019). While more work is required, collectively these studies have revealed several potential protein biomarkers of PMI that may be useful in death investigations. Furthermore, since the proteome can be used to characterize the function of an environment of interest (Aslam et al. 2017), this method could simultaneously shed light on the ecology of decomposition. One notable caveat is that the use of proteomics is limited to those who can afford to access specialized facilities that are properly equipped with the necessary software, databases, and trained personnel (Aslam et al. 2017). For this technique to be developed into a practical forensic tool, future research should include experimentation on more timeframes of decomposition (e.g., after one year), incorporation of sample types other than bone, and a transition of studies that focus on human decomposer proteomes.

Volatile Organic Compounds

Vertebrate decomposition is often associated with a distinct odor, which attracts necrophagous insects and scavengers to the cadaver. Microbial enzyme-induced decomposition of organic matter results in the production and release of volatile organic compounds (VOCs) into the surrounding environment (Forbes and Perrault 2014), which undergo an “odor evolution” with increasing PMI (Verheggen et al. 2017). There is a wide variety of VOCs produced from degraded proteins, carbohydrates, and fats in the human body, including chemical classes such as alkanes, alcohols, esters, ketones, aldehydes, cyclic hydrocarbons, aromatic compounds, and sulfur- and hydrogen-containing compounds (Stefanuto et al. 2015). In the forensic sciences, these odors have been profiled for the purposes of understanding the role of abiotic factors on VOCs (Kasper et al. 2012), locating graves (Armstrong et al. 2016; Forbes and Perrault 2014; Hoffman et al. 2009; Irish et al. 2019; Perrault et al. 2015; Stadler et al. 2013) and estimating PMI (Paczkowski et al. 2015; Vass 2017; Xia et al. 2019). The volatiles can be collected by several methods, the most common of which include solid phase microextraction and use of sorbent tubes to collect air from the headspace of the cadaver (Verheggen et al. 2017). Analysis of VOCs is then typically carried out using gas chromatography to separate the compounds and mass spectrometry to detect them (GC-MS) (Iqbal et al. 2017; Verheggen et al. 2017). These analyses have been performed on a variety of sample types from several different model organisms within the laboratory and in the field, including air, soil, and tissue collected from mice, rats, pigs, cattle (*Bos taurus*), and human cadavers (Iqbal et al. 2017; Verheggen et al. 2017). To determine which volatiles are most predictive of PMI, Paczkowski et al. (2015) found VOCs from decomposing pigs to correlate with increased decomposition, including hexanal, nonanal, dimethyl disulfide, dimethyl trisulfide, 1-butanol, and phenol. Other analyses have indicated that volatile fatty acids such as propionic, butyric, and valeric acid may be indicators of PMI (Vass 2017). The VOCs most reported to be associated with decomposition odor were polysulfide compounds like dimethyl sulfide (DMS), dimethyl disulfide (DMDS), and dimethyl trisulfide (DMTS) (Verheggen et al. 2017). Another study found 15 different VOCs from decomposing rat muscle correlated with PMI, which were used in a "fingerprinting" analysis to produce a PMI error of 0.5 days over 10 days of decomposition (Xia et al. 2019). This indicates that a combination of VOC indicators may be better for estimating PMI compared to a single compound. While this research has revealed several potential biomarkers of PMI, more studies on human cadavers are required before this method can be validated and implemented into applied forensics.

Using Skeletal Remains for Estimating Late PMI

If remains are discovered after a long enough period of decomposition, often the only tissues that remain are those of bones and teeth. When there is no other evidence associated with the decedent, investigators must use what is available to them, and the stability of bones and teeth over time makes them a potentially untapped resource for estimating PMI via biomolecular or other methods. Currently, a common way of estimating the PMI of skeletal remains involves a careful visual assessment of the degree of soft tissue that remains and the overall condition of the bones by trained professionals (Dirkmaat and Cabo 2016). While there is some ongoing work in this field, this can become increasingly complex, with substantial room for error, when considering the extent of bone subaerial weathering (Chapter 11), the presence of vegetation, and the environmental conditions inflicted upon the decedent (Procopio et al. 2018b).

A variety of other methods have also been pursued to develop a tool to reliably estimate the PMI of skeletal remains. For example, researchers have tried correlating the degradation of bone DNA with PMI (Hagelberg et al. 1991; Perry 1988), but the accuracy of this method has varied based on climate, temperature, moisture content, whether the decedent was buried, the pH of the soil (if applicable) (Haslam and Tibbett 2009), and likely many other unknown factors. More recently, researchers have employed a diversity of fluorescence and microscopic imaging techniques (Amadasi et al. 2017; Creagh and Cameron 2017; Hoke et al. 2013; Longato et al. 2015; Woess et al. 2017). In addition, some of the biomolecular techniques described above have also been applied to bone for late PMI estimations. Since microbes can invade and degrade bone during decomposition (Child 1995a, b; Hackett 1981; Turner-Walker 2008), researchers have begun assessing whether a predictable succession of the rib bone microbial decomposer community would be a reliable estimator of late PMI (Damann et al. 2015). Others have utilized proteomics for the identification of potential protein biomarkers of PMI in bone (see "Biomolecular Methods" section, above) (Procopio et al. 2018b). The tested timeframes of decomposition in each of the above studies, however, ranges from days to years, with little consensus regarding when and how bone is most useful for estimating PMI. In addition, while these studies have highlighted several promising approaches to estimate PMI, thus far none have developed a working forensic tool. To move beyond the use of unreliable visual assessments, further investigation into each of these methods is required, with a focus on greater sample sizes using human remains, increased standardization of associated methods/techniques, and a greater consistency of the decomposition timeframe.

Estimating the PMI of Buried Remains

The burial of remains introduces several extra variables to consider within the already complex decomposition ecosystem (Chapter 5). The burial environment is a dynamic system of chemical, physical, and biological processes that influence decay (Collins et al. 2002; Haslam and Tibbett 2009; Hedges 2002). In addition to the climate of the surface environment, factors such as soil type, pH, moisture content, oxygen levels, and the depth of the burial can all affect the preservation of the remains (Carter et al. 2008, 2010; Haslam and Tibbett 2009; Marais-Werner et al. 2017; Vass 2011). Furthermore, the remains are less accessible to insect activity, making entomological evidence a less reliable source of evidence (Bishop 2015; Ferreira and Cunha 2013; Pittner et al. 2020). Similar to late PMI methods, most current methods for determining the PMI of buried remains rely on grading the visual characteristics (Dirkmaat and Cabo 2016; Pittner et al. 2020). When forced to consider the plethora of variables that influence preservation, in practice this is increasingly inaccurate and varies based on the scoring method used (see "Macroscopic Tissue Changes and Universal Models" section, above), especially for buried remains (Ferreira and Cunha 2013; Pittner et al. 2020). Some attempts to develop formulae for estimating the PMI in burial context have been proposed (Bishop 2015; Vass 2011), but further development and extensive experimental validation is needed for any formula to account for all necessary decomposition variables (Cockle and Bell 2015).

Some of the other previously described methods for estimating PMI have also been used in burial contexts. Due to the preservation of bone protein (Collins et al. 2002), researchers have tried proteomics to estimate the PMI of buried remains. As described above, Procopio et al. (2018b) found this technique to be a promising method for estimating the PMI of bone from buried pigs. Experimental methods like citrate content have been found to underestimate PMI (Kanz et al. 2014), while others like FTIR spectroscopy and chemometrics have shown potential for estimating the PMI of buried remains (Wang et al. 2017). Other newer methods are microbial based. Procopio et al. (2018a) discovered that some phyla (Proteobacteria, Firmicutes, Bacteroidetes, and Acidobacteria) trend with PMI in the soil communities of buried pigs. Pittner et al. (2020) used a combination of methods and found that while proteomics would be useful for up to 28 days of buried decomposition, microbial succession data are valuable for at least three months postmortem. Despite the increased complexity of estimating the PMI of buried remains, researchers have made substantial progress. Like all of the previously described methods, future studies focusing on increased sample sizes of human remains with data-driven PMI estimates would aid in the development of an accurate and functional PMI model.

Conclusion

Though often described using stage-based systems, vertebrate decomposition is a complicated and dynamic process that does not fit neatly into defined categories. Decomposition is influenced by intrinsic and extrinsic factors that increase or decrease the rate of decomposition and/or alter the trajectory of decomposition events. The development of methods used to quantify the degree of decomposition (e.g., mass loss, TBS, TBDS, etc.) has been essential to our understanding of the progression of decomposition under a number of environmental conditions. Though research conducted on animals and humans, paired with many of these methods, has greatly improved our understanding of the pattern and rate of decomposition and the impact of biological, environmental, behavioral, and cultural factors, much remains to be learned. A more holistic, systems-based approach to understanding decomposition chemistry, biology, and ecology, fostered by interdisciplinary collaboration, is likely to be instrumental to the field. Despite the complex dynamics of vertebrate decomposition, there is a succession of interacting insects, microbes, and other scavengers and biomolecular components that researchers are beginning to understand and exploit for the development of a PMI estimation model. There needs to be an emphasis on methods standardization and validation for methods of PMI estimation to be adapted and used in applied forensic contexts. Too often, research falls to the wayside and fails to be validated, or if it is validated, the methods used are inconsistent between studies, from sample collection to statistical methods such as data transformations. Furthermore, if PMI estimation methods are to be used to predict the PMI of human remains, methods need to be validated using human remains with adequate sample sizes. This will likely be facilitated by further expansion of human decomposition research facilities globally and increased collaboration with medicolegal investigators.

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References

Adlam, R. E., and T. Simmons (2007) The effect of repeated physical disturbance on soft tissue decomposition—Are taphonomic studies an accurate reflection of decomposition? *Journal of Forensic Sciences* 52(5):1007–1014.

Aitkenhead-Peterson, J. A., C. G. Owings, M. B. Alexander, N. Larison, and J. A. Bytheway (2012) Mapping the lateral extent of human cadaver decomposition with soil chemistry. *Forensic Science International* 216(1–3):127–134.

Amadasi, A., A. Cappella, C. Cattaneo, P. Cofrancesco, L. Cucca, D. Merli, and C. Milanese (2017) Determination of the post mortem interval in skeletal remains by the comparative use of different physico-chemical methods: Are they reliable as an alternative to 14C? *Homo* 68(3):213–221.

Anderson, G. S. (2000) Minimum and maximum development rates of some forensically important Calliphoridae (Diptera). *Journal of Forensic Sciences* 45(4):824–832

Anderson, G. S. (2011) Comparison of decomposition rates and faunal colonization of carrion in indoor and outdoor environments. *Journal of Forensic Sciences* 56(1):136–142.

Anderson, G. S., P. S. Barton, M. Archer, and J. R. Wallace (2019) Invertebrate scavenging communities. In *Carrion Ecology and Management* ed. by P. P. Olea, P. Mateo-Tomás, and J. A. Sánchez Zapata, pp. 45–69. Springer, Cham, Switzerland.

Armstrong, P., K. D. Nizio, K. A. Perrault, and S. L. Forbes (2016) Establishing the volatile profile of pig carcasses as analogues for human decomposition during the early postmortem period. *Heliyon* 2(2):70.

Aslam, B., M. Basit, M. A. Nisar, M. Khurshid, and M. H. Rasool (2017) Proteomics: Technologies and their applications. *Journal of Chromatographic Science* 55(2):182–196.

Bachmann, J., and T. Simmons (2010) The influence of preburial insect access on the decomposition rate. *Journal of Forensic Sciences* 55(4):893–900.

Barton, P. S., M. J. Evans, C. N. Foster, J. L. Pechal, J. K. Bump, M. M. Quaggiotto, and M. E. Benbow (2019) Towards quantifying carrion biomass in ecosystems. *Trends in Ecology and Evolution* 34(10):950–961.

Barton, P. S., S. McIntyre, M. J. Evans, J. K. Bump, S. A. Cunningham, and A. D. Manning (2016) Substantial long-term effects of carcass addition on soil and plants in a grassy eucalypt woodland. *Ecosphere* 7(10):1–11.

Bates, L. N., and D. J. Wescott (2016) Comparison of decomposition rates between autopsied and non-autopsied human remains. *Forensic Science International* 261:93–100.

Bauer, A., A. M. Bauer, and J. K. Tomberlin (2020) Impact of diet moisture on the development of the forensically important blow fly *Cochliomyia macellaria* (Fabricius) (Diptera: Calliphoridae). *Forensic Science International* 312:110333. DOI: 10.1016/j.forsciint.2020.110333.

Belk, A. D., H. L. Deel, Z. M. Burcham, R. Knight, D. O. Carter, and J. L. Metcalf (2018a) Animal models for understanding microbial decomposition of human remains. *Drug Discovery Today: Disease Models* 28:117–125.

Belk, A., Z. Z. Xu, D. O. Carter, A. Lynne, S. Bucheli, R. Knight, and J. L. Metcalf (2018b) Microbiome data accurately predicts the postmortem interval using random forest regression models. *Genes* 9(2):104. DOI: 10.3390/genes9020104.

Benbow, M. E., A. J. Lewis, J. K. Tomberlin, and J. L. Pechal (2013) Seasonal necrophagous insect community assembly during vertebrate carrion decomposition. *Journal of Medical Entomology* 50(2):440–450.

Bishop, C. P. (2015) Estimating Postmortem Interval: A Molecular Approach. National Institute of Justice, award number 2010-DN-BX-K180. Electronic document, https://www.ncjrs.gov/pdffiles1/nij/grants/248959.pdf, accessed 27 February 2021.

Bourel, B., V. Hédouin, L. Martin-Bouyer, A. Bécart, G. Tournel, M. Deveaux, and D. Gosset (1999) Effects of morphine in decomposing bodies on the development of *Lucilia sericata* (Diptera: Calliphoridae). *Journal of Forensic Sciences* 44(2):354–358.

Browne, B. L. (1962) The relationship between oviposition in the blowfly *Lucilia cuprina* and the presence of water. *Journal of Insect Physiology* 8(4):383–390.

Buckley, M., and C. Wadsworth (2014) Proteome degradation in ancient bone: Diagenesis and phylogenetic potential. *Palaeogeography, Palaeoclimatology, Palaeoecology* 416:69–79.

Burcham, Z. M., C. A. Cowick, C. N. Baugher, J. L. Pechal, C. J. Schmidt, J. W. Rosch, M. E. Benbow, and H. R. Jordan (2019) Total RNA analysis of bacterial community structural and functional shifts throughout vertebrate decomposition. *Journal of Forensic Sciences* 64(6): 1707–1719.

Byard, R. W., E. Simpson, and S. L. Forbes (2020) Arid climate adipocere: The importance of microenvironment. *Journal of Forensic Sciences* 65(1):327–329.

Campobasso, C. Pietro, G. Di Vella, and F. Introna (2001) Factors affecting decomposition and Diptera colonization. *Forensic Science International* 120(1–2):18–27.

Cappellini, E., L. J. Jensen, D. Szklarczyk, A. Ginolhac, R. A. R. Fonseca, T. W. Stafford, and S. R. Holen (2012) Proteomic analysis of a Pleistocene mammoth femur reveals more than one hundred ancient bone proteins. *Journal of Proteome Research* 11(2):917–926.

Carter, D. O., J. L. Metcalf, A. Bibat, and R. Knight (2015) Seasonal variation of postmortem microbial communities. *Forensic Science, Medicine, and Pathology* 11(2):202–207.

Carter, D. O., D. Yellowlees, and M. Tibbett (2007) Cadaver decomposition in terrestrial ecosystems. *Naturwissenschaften* 94(1):12–24.

Carter, D. O., D. Yellowlees, and M. Tibbett (2008) Temperature affects microbial decomposition of cadavers (*Rattus rattus*) in contrasting soils. *Applied Soil Ecology* 40(1):129–137.

Carter, D. O., D. Yellowlees, and M. Tibbett (2010) Moisture can be the dominant environmental parameter governing cadaver decomposition in soil. *Forensic Science International* 200(1–3):60–66.

Ceciliason, A. S., M. G. Andersson, A. Lindström, and H. Sandler (2018) Quantifying human decomposition in an indoor setting and implications for postmortem interval estimation. *Forensic Science International* 283:180–189. DOI: 10.1016/j.forsciint.2017.12.026.

Child, A. M. (1995a) Microbial taphonomy of archaeological bone. *Studies in Conservation* 40(1):19–30.

Child, A. M. (1995b) Towards an understanding of the microbial decomposition of archaeological bone in the burial environment. *Journal of Archaeological Science* 22(2):165–174.

Choi, K.-M., A. Zissler, E. Kim, B. Ehrenfellner, E. Cho, S.-I. Lee, P. Steinbacher, K. N. Yun, J. H. Shin, J. Y. Kim, W. Stoiber, H. Chung, F. C. Monticelli, J.-Y. Kim, and S. Pittner (2019) Postmortem proteomics to discover biomarkers for forensic PMI estimation. *International Journal of Legal Medicine* 133(3):899–908.

Clark, M., M. Worrel, and J. Pless (1997) Postmortem changes in soft tissues. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 151–164. CRC Press, Boca Raton, FL.

Clarke, T. H., A. Gomez, H. Singh, K. E. Nelson, and L. M. Brinkac (2017) Integrating the microbiome as a resource in the forensics toolkit. *Forensic Science International: Genetics* 30:141–147. DOI: 10.1016/j.fsigen.2017.06.008.

Cobaugh, K. L., S. M. Schaeffer, and J. M. DeBruyn (2015) Functional and structural succession of soil microbial communities below decomposing human cadavers. *PLoS ONE* 10(6):e0130201. DOI: 10.1371/journal.pone.0130201.

Cockle, D. L., and L. S. Bell (2015) Human decomposition and the reliability of a 'Universal' model for post mortem interval estimations. *Forensic Science International* 253:136.e1–136.e9.

Cockle, D. L., and L. S. Bell (2019) The impact of trauma and blood loss on human decomposition. *Science and Justice* 59(3):332–336.

Collins, M. J., C. M. Nielsen-Marsh, J. Hiller, C. I. Smith, J. P. Roberts, R. V. Prigodich, T. J. Wess, J. Csapò, A. R. Millard, and G. Turner-Walker (2002) The survival of organic matter in bone: A review. *Archaeometry* 44(3):383–394.

Connor, M., C. Baigent, and E. S. Hansen (2018) Testing the use of pigs as human proxies in decomposition studies. *Journal of Forensic Sciences* 63(5):1350–1355.

Connor, M., C. Baigent, and E. S. Hansen (2019) Measuring desiccation using qualitative changes: A step toward determining regional decomposition sequences. *Journal of Forensic Sciences* 64(4):1004–1011.

Creagh, D., and A. Cameron (2017) Estimating the post-mortem interval of skeletonized remains: The use of infrared spectroscopy and Raman spectro-microscopy. *Radiation Physics and Chemistry* 137:225–229.

Cross, P., and T. Simmons (2010) The influence of penetrative trauma on the rate of decomposition. *Journal of Forensic Sciences* 55(2):295–301.

Dabbs, G. R., M. Connor, and J. A. Bytheway (2016) Interobserver reliability of the Total Body Score System for quantifying human decomposition. *Journal of Forensic Sciences* 61(2):445–451.

Damann, F. E., A. Tanittaisong, and D. O. Carter (2012) Potential carcass enrichment of the University of Tennessee Anthropology Research Facility: A baseline survey of edaphic features. *Forensic Science International* 222(1–3):4–10.

Damann, F. E., D. E. Williams, and A. C. Layton (2015) Potential use of bacterial community succession in decaying human bone for estimating postmortem interval. *Journal of Forensic Sciences* 60(4):844–850.

Dautartas, A., M. W. Kenyhercz, G. M. Vidoli, L. Meadows Jantz, A. Mundorff, and D. W. Steadman (2018) Differential decomposition among pig, rabbit, and human remains. *Journal of Forensic Sciences* 63(6):1673–1683.

Davidson, E. A., and I. A. Janssens (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440(7081):165–173.

De Jong, G. D., W. W. Hoback, and L. G. Higley (2011) Effect of investigator disturbance in experimental forensic entomology: Carcass biomass loss and temperature. *Journal of Forensic Sciences* 56(1):143–149.

DeBruyn, J. M., and K. A. Hauther (2017) Postmortem succession of gut microbial communities in deceased human subjects. *PeerJ* 5:e3437. DOI: 10.7717/peerj.3437.

DeBruyn, J. M., K. M. Hoeland, L. S. Taylor, J. D. Stevens, M. A. Moats, S. Bandopadhyay, S. P. Dearth, H. F. Castro, K. K. Hewitt, S. R. Campagna, A. M. Dautartas, G. M. Vidoli, A. Z. Mundorff, and D. W. Steadman (2021) Comparative decomposition of humans and pigs: Soil biogeochemistry, microbial activity and metabolomic profiles. *Frontiers in Microbiology* 11:608856. DOI: 10.3389/fmicb.2020.608856.

DeVault, T. L., I. L. Brisbin, and O. E. Rhodes (2004) Factors influencing the acquisition of rodent carrion by vertebrate scavengers and decomposers. *Canadian Journal of Zoology* 82(3):502–509.

DeVault, T. L., O. E. Rhodes, and J. A. Shivik (2003) Scavenging by vertebrates: Behavioral, ecological, and evolutionary perspectives on an important energy transfer pathway in terrestrial ecosystems. *Oikos* 102(2):225–234.

Dirkmaat, D. C., and L. L. Cabo (2016) Forensic archaeology and forensic taphonomy: Basic considerations on how to properly process and interpret the outdoor forensic scene. *Academic Forensic Pathology* 6(3):439–454.

Efremov, J. A. (1940) Taphonomy: A new branch of paleontology. *Pan-American Geologist* 74(2):81–93.

Fancher, J. P., J. A. Aitkenhead-Peterson, T. Farris, K. Mix, A. P. Schwab, D. J. Wescott, and M. D. Hamilton (2017) An evaluation of soil chemistry in human cadaver decomposition islands: Potential for estimating postmortem interval (PMI). *Forensic Science International* 279:130–139. DOI: 10.1016/j.forsciint.2017.08.002.

Ferreira, M. T., and E. Cunha (2013) Can we infer post mortem interval on the basis of decomposition rate? A case from a Portuguese cemetery. *Forensic Science International* 226(1–3):298.e1–298.e6.

Fiedler, S., and M. Graw (2003) Decomposition of buried corpses, with special reference to the formation of adipocere. *Naturwissenschaften* 90(7):291–300.

Fierer, N., C. L. Lauber, N. Zhou, D. McDonald, E. K. Costello, and R. Knight (2010) Forensic identification using skin bacterial communities. *Proceedings of the National Academy of Sciences of the United States of America* 107(14):6477–6481.

Finley, S. J., J. L. Pechal, M. E. Benbow, B. K. Robertson, and G. T. Javan (2016) Microbial signatures of cadaver gravesoil during decomposition. *Microbial Ecology* 71(3):524–529.

Fitzgerald, C. M., and M. Oxenham (2009) Modelling time-since-death in Australian temperate conditions. *Australian Journal of Forensic Sciences* 41(1):27–41.

Forbes, S. L., and D. O. Carter (2016) Processes and mechanisms of death and decomposition of vertebrate carrion. In *Carrion Ecology, Evolution, and Their Applications* ed. by M. E. Benbow, J. K. Tomberlin, and A. M. Tarone, pp. 13–30. CRC Press, Boca Raton, FL.

Forbes, M. N. S., D. A. Finaughty, K. L. Miles, and V. E. Gibbon (2019) Inaccuracy of accumulated degree day models for estimating terrestrial post-mortem intervals in Cape Town, South Africa. *Forensic Science International* 296:67–73.

Forbes, S. L, and K. A. Perrault (2014) Decomposition odour profiling in the air and soil surrounding vertebrate carrion. *PLoS ONE* 9(4):95107. DOI: 10.1371/journal.pone.0095107.

Forbes, S. L., K. A. Perrault, and J. L. Comstock (2017) Microscopic post-mortem changes: The chemistry of decomposition. In *Taphonomy of Human Remains: Forensic Analysis of the Dead and the Depositional Environment* ed. by E. M. J. Schotsmans, N. Márquez-Grant, and S. L. Forbes, pp. 26–38. Wiley, Chichester, UK.

Forbes, S. L., B. H. Stuart, I. R. Dadour, and B. B. Dent (2004) A preliminary investigation of the stages of adipocere formation. *Journal of Forensic Sciences* 49(3):566–574.

Forbes, S. L, B. H. Stuart, and B. B. Dent (2005) The effect of the burial environment on adipocere formation. *Forensic Science International* 154(1):24–34.

Galloway, A., W. H. Birkby, A. M. Jones, T. E. Henry, and B. O. Parks (1989) Decay rates of human remains in an arid environment. *Journal of Forensic Sciences* 34(3):607–616.

Gelderman, H. T., L. Boer, T. Naujocks, A. C. M. Ijzermans, and W. L. J. M. Duijst (2018) The development of a post-mortem interval estimation for human remains found on land in the Netherlands. *International Journal of Legal Medicine* 132(3):863–873.

Gill-King, H. (1997) Chemical and ultrastructural aspects of decomposition. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W D. Haglund and M. H. Sorg, pp. 93–108. CRC Press, Boca Raton, FL.

Goff, M. L. (1991) Comparison of insect species associated with decomposing remains recovered inside dwellings and outdoors on the island of Oahu, Hawaii. *Journal of Forensic Sciences* 36(3):748–753.

Goff, M. L. (2009) Early post-mortem changes and stages of decomposition in exposed cadavers. *Experimental and Applied Acarology* 49(1–2):21–36.

Hackett, C. J. (1981) Microscopical focal destruction (tunnels) in exhumed human bones. *Medical Science and Law* 21(4):243–265.

Hagelberg, E., L. S. Bell, T. Allen, A. Boyde, S. J. Jones, and J. B Clegg (1991) Analysis of ancient bone DNA: techniques and applications. *Philosophical Transactions of the Royal Society, London* 333:399–407.

Haglund, W. D., and M. H. Sorg (1997a) Introduction to forensic taphonomy. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 1–9. CRC Press, Boca Raton, FL.

Haglund, W. D., and M. H. Sorg (1997b) Method and theory of forensic taphonomy research. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 13–25. CRC Press, Boca Raton, FL.

Haslam, T. C. F., and N. Tibbett (2009) Soils of contrasting pH affect the decomposition of buried mammalian (*Ovis aries*) skeletal muscle tissue. *Journal of Forensic Sciences* 54(4):900–904.

Hauther, K. A., K. L. Cobaugh, L. M. Jantz, T. E. Sparer, and J. M. DeBruyn (2015) Estimating time since death from postmortem human gut microbial communities. *Journal of Forensic Sciences* 60(5):1234–1240.

Hedges, R. E. M. (2002) Bone diagenesis: An overview of processes. *Archaeometry* 44:319–328.

HMP Consortium (2012) Structure, function and diversity of the healthy human microbiome. *Nature* 486(7402):207–214.

Hoffman, E. M., A. M. Curran, N. Dulgerian, R. A. Stockham, and B. A. Eckenrode (2009) Characterization of the volatile organic compounds present in the headspace of decomposing human remains. *Forensic Science International* 186(1–3):6–13.

Hoke, N., A. Grigat, G. Grupe, and M. Harbeck (2013) Reconsideration of bone postmortem interval estimation by UV-induced autofluorescence. *Forensic Science International* 228(1–3):176e1–176e6.

Iqbal, M. A., K. D. Nizio, M. Ueland, and S. L. Forbes (2017) Forensic decomposition odour profiling: A review of experimental designs and analytical techniques. *Trends in Analytical Chemistry* 91:112–124.

Irish, L., S. R. Rennie, G. M. B. Parkes, and A. Williams (2019) Identification of decomposition volatile organic compounds from surface-deposited and submerged porcine remains. *Science and Justice* 59(5):503–515.

Janaway, R. C., S. L. Percival, and A. S. Wilson, (2009) Decomposition of human remains. In *Microbiology and Aging: Clinical Manifestations* ed. by S. L. Percival, pp. 313–334. Springer, New York.

Javan, G. T., S. J. Finley, I. Can, J. E. Wilkinson, J. D. Hanson, and A. M. Tarone (2016) Human thanatomicrobiome succession and time since death. *(Nature) Scientific Reports* 6(1):29598.

Jeong, Y., L. M. Jantz, and J. Smith (2016) Investigation into seasonal scavenging patterns of raccoons on human decomposition. *Journal of Forensic Sciences* 61(2):467–471.

Jordan, H. R., J. K. Tomberlin, T. K. Wood, and M. E. Benbow (2016) Interkingdom ecological interactions of carrion decomposition. In *Carrion Ecology, Evolution, and their Applications* ed. by M. E. Benbow, J. K. Tomberlin, and A. M. Tarone, pp. 433–459. CRC Press, Boca Raton, FL.

Kanz, F., C. Reiter, and D. U. Risser (2014) Citrate content of bone for time since death estimation: Results from burials with different physical characteristics and known PMI. *Journal of Forensic Sciences* 59(3):613–620.

Kasper, J., R. Mumm, and J. Ruther (2012) The composition of carcass volatile profiles in relation to storage time and climate conditions. *Forensic Science International* 223(1–3):64–71.

Keenan, S. (2016) From bone to fossil: A review of the diagenesis of bioapatite. *American Mineralogist* 101(9):1943–1951.

Keenan, S. W., A. L. Emmons, L. S. Taylor, G. Phillips, A. R. Mason, A. Z. Mundorff, E. C. Bernard, J. Davoren, and J. M. DeBruyn (2018) Spatial impacts of a multi-individual grave on microbial and microfaunal communities and soil biogeochemistry. *PLoS ONE* 13(12):e0208845. DOI: 10.1371/journal.pone.0208845.

Kelly, J. A., T. C. Van Der Linde, and G. S. Anderson (2009) The influence of clothing and wrapping on carcass decomposition and arthropod succession during the warmer seasons in Central South Africa. *Journal of Forensic Sciences* 54(5):1105–1112.

Kendall, C., A. Marie, H. Eriksen, I. Kontopoulos, M. J. Collins, and G. Turner-Walker (2018) Diagenesis of archaeological bone and tooth. *Palaeogeography, Palaeoclimatology, Palaeoecology* 491:21–37.

Kikuchi, K., K.-I. Kawahara, K. K. Biswas, T. Ito, S. Tancharoen, N. Shiomi, and Y. Koda (2010) HMGB1: A new marker for estimation of the postmortem interval. *Experimental and Therapeutic Medicine* 1(1):109–111.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel (2006) World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* 15(3):259–263.

Langley, N. R., P. Wood, P. Herring, and D. W. Steadman (2019) Forensic postmortem interval estimation from skeletal muscle tissue: A lipidomics approach. *Forensic Anthropology* 2(3):152–157.

Lauber, C. L., J. L. Metcalf, K. Keepers, G. Ackermann, D. O. Carter, and R. Knight (2014) Vertebrate decomposition is accelerated by soil microbes. *Applied and Environmental Microbiology* 80(16):4920–4929.

Lax, S., J. T. Hampton-Marcell, S. M. Gibbons, G. B. Colares, D. Smith, J. A. Eisen, and J. A. Gilbert (2015) Forensic analysis of the microbiome of phones and shoes. *Microbiome* 3(1):21. DOI: 10.1186/s40168-015-0082-9.

Lennartz, A., M. Hamilton, and R. Weaver (2020) Moisture content in decomposing, desiccated, and mummified human tissue. *Forensic Anthropology* 3(1):1–16.

Longato, S., C. Wöss, P. Hatzer-Grubwieser, C. Bauer, W. Parson, S. H. Unterberger, and V. Kuhn (2015) Post-mortem interval estimation of human skeletal remains by micro-computed tomography, mid-infrared microscopic imaging and energy dispersive X-ray mapping. *Analytical Methods* 7(7):2917–2927.

Ma, Q., A. Fonseca, W. Liu, A. T. Fields, M. L. Pimsler, A. F. Spindola, A. M. Tarone, T. L. Crippen, J. K. Tomberlin, and T. K. Wood (2012) *Proteus mirabilis* interkingdom swarming signals attract blow flies microbe-microbe and microbe-host interactions. *The ISME Journal* 6(7):1356–1366.

Madea, B. (2016) Methods for determining time of death. *Forensic Science, Medicine, and Pathology* 12(4):451–485.

Maile, A. E., C. G. Inoue, L. E. Barksdale, and D. O. Carter (2017) Toward a universal equation to estimate postmortem interval. *Forensic Science International* 272:150–153.

Mann, R. W., W. M. Bass, and L. Meadows (1990) Time since death and decomposition of the human body: Variables and observations in case and experimental field studies. *Journal of Forensic Sciences* 35(1):103–111.

Marais-Werner, A., J. Myburgh, A. Meyer, W. C. Nienaber, and M. Steyn (2017) Decomposition patterns of buried remains at different intervals in the Central Highveld region of South Africa. *Medicine, Science, and the Law* 57(3):115–123.

Marhoff-Beard, S. J., S. L. Forbes, and H. Green (2018) The validation of 'universal' PMI methods for the estimation of time since death in temperate Australian climates. *Forensic Science International* 291:158–166.

Marks, M. K., J. C. Love, and I. R. Dadour (2009) Taphonomy and time: Estimating the postmortem interval. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 165–178. Prentice Hall, Upper Saddle River, NJ.

Matuszewski, S., M. J. R. Hall, G. Moreau, K. G. Schoenly, A. M. Tarone, and M. H. Villet (2020) Pigs vs people: The use of pigs as analogues for humans in forensic entomology and taphonomy research. *International Journal of Legal Medicine* 134(2):793–810.

Matuszewski, S., S. Konwerski, K. Frątczak, and M. Szafałowicz (2014) Effect of body mass and clothing on decomposition of pig carcasses. *International Journal of Legal Medicine* 128(6):1039–1048.

Megyesi, M. S., S. P. Nawrocki, and N. H. Haskell (2005) Using Accumulated Degree-Days to estimate the postmortem interval from decomposed human remains. *Journal of Forensic Sciences* 50(3):618–626.

Metcalf, J. L. (2019) Estimating the postmortem interval using microbes: Knowledge gaps and a path to technology adoption. *Forensic Science International: Genetics* 38:211–218.

Metcalf, J. L., L. W. Parfrey, A. Gonzalez, C. L. Lauber, D. Knights, G. Ackermann, G. C. Humphrey, M. J. Gebert, W. Van Treuren, D. Berg-Lyons, K. Keepers, Y. Guo, J. Bullard, N. Fierer, D. O. Carter, and R. Knight (2013) A microbial clock provides an accurate estimate of the postmortem interval in a mouse model system. *eLife* 2:e01104. DOI: 10.7554/eLife.01104.

Metcalf, J. L., Z. Z. Xu, S. Weiss, S. Lax, W. Van Treuren, E. R. Hyde, S. J. Song, A. Amir, P. Larsen, N. Sangwan, D. Haarmann, G. C. Humphrey, G. Ackermann, L. R. Thompson, C. Lauber, A. Bibat, C. Nicholas, M. J. Gebert, J. F. Petrosino, S. C. Reed, J. A. Gilbert, A. M. Lynne, S. R. Bucheli, D. O. Carter, and R. Knight (2016) Microbial community assembly and metabolic function during mammalian corpse decomposition. *Science* 351(6269):158–162.

Michaud, J.-P., K. G. Schoenly, and G. Moreau (2012) Sampling flies or sampling flaws? Experimental design and inference strength in forensic entomology. *Journal of Medical Entomology* 49(1):1–10.

Micozzi, M. S. (1986) Experimental study of postmortem change under field conditions: Effects of freezing, thawing, and mechanical injury. *Journal of Forensic Sciences* 31(3):953–961.

Moffatt, C., T. Simmons, and J. Lynch-Aird (2016) An improved equation for TBS and ADD: Establishing a reliable postmortem interval framework for casework and experimental studies. *Journal of Forensic Sciences* 61(S1):S201–S207.

Myburgh, J., E. N. L'Abbé, M. Steyn, and P. J. Becker (2013) Estimating the postmortem interval (PMI) using Accumulated Degree-Days (ADD) in a temperate region of South Africa. *Forensic Science International* 229:165.e1–e6.

National Oceanographic and Atmospheric Administration (NOAA) (2021) Data Tools: Local Climatological Data (LCD). Electronic document, https://www.ncdc.noaa.gov/cdo-web/datatools/lcd, accessed 7 February 2021.

Oostra, R. J., T. Gelderman, W. J. M. Groen, H. G. Uiterdijk, E. L. H. Cammeraat, T. Krap, L. S. Wilk, M. Lüschen, W. E. Morriën, F. Wobben, W. L. J. M. Duijst, and M. C. G. Aalders (2020) Amsterdam Research Initiative for Sub-surface Taphonomy and Anthropology (ARISTA)—A taphonomic research facility in the Netherlands for the study of human remains. *Forensic Science International* 317:110483.

Paczkowski, S., S. Nicke, H. Ziegenhagen, and S. Schütz (2015) Volatile emission of decomposing pig carcasses (*Sus scrofa domesticus* L.) as an indicator for the postmortem interval. *Journal of Forensic Sciences* 60(S1):S130–S137.

Parmenter, R. R., and J. A. MacMahon (2009) Carrion decomposition and nutrient cycling in a semiarid shrub-steppe ecosystem. *Ecological Monographs* 79(4):637–661.

Payne, J. A. (1965) A summer carrion study of the baby pig *Sus scrofa* Linnaeus. *Ecology* 46(5):592–602.

Pechal, J. L., M. E. Benbow, T. L. Crippen, A. M. Tarone, and J. K. Tomberlin (2014a) Delayed insect access alters carrion decomposition and necrophagous insect community assembly. *Ecosphere* 5(4):1–21.

Pechal, J. L., T. L. Crippen, M. E. Benbow, A. M. Tarone, S. Dowd, and J. K. Tomberlin (2014b) The potential use of bacterial community succession in forensics as described by high throughput metagenomic sequencing. *International Journal of Legal Medicine* 128(1):193–205.

Pechal, J. L., C. J. Schmidt, H. R. Jordan, and M. E. Benbow (2018) A large-scale survey of the postmortem human microbiome, and its potential to provide insight into the living health condition. *(Nature) Scientific Reports* 8(5724). DOI: 10.1038/s41598-018-23989-w.

Pecsi, E. L., G. Bronchti, F. Crispino, and S. L. Forbes (2020) Perspectives on the establishment of a Canadian human taphonomic facility: The experience of REST[ES]. *Forensic Science International: Synergy* 2:287–292.

Perrault, K. A., P.-H. Stefanuto, B. H. Stuart, T. Rai, J.-F. Focant, and S. L. Forbes (2015) Detection of decomposition volatile organic compounds in soil following removal of remains from a surface deposition site. *Forensic Science, Medicine, and Pathology* 11(3):376–387.

Perry, W. L., W. M. Bass, W. S. Riggsby, and K. Sirotkin (1988) The autodegradation of deoxyribonucleic acid (DNA) in human rib bone and its relationship to the time interval since death. *Journal of Forensic Sciences* 33(1):144–153.

Pittner, S., V. Bugelli, M. E. Benbow, B. Ehrenfellner, A. Zissler, C. P. Campobasso, R.-J. Oostra, M. C. G. Aalders, R. Zehner, L. Lutz, F. C. Monticelli, C. Staufer, K. Helm, V. Pinchi, J. P. Receveur, J. Geißenberger, P. Steinbacher, and J. Amendt (2020) The applicability of forensic time since death estimation methods for buried bodies in advanced decomposition stages. *PLoS ONE* 15(12):1–26. DOI: 10.1371/journal.pone.0243395.

Procopio, N., A. T. Chamberlain, and M. Buckley (2017) Intra- and interskeletal proteome variations in fresh and buried bones. *Journal of Proteome Research* 16(5):2016–2209.

Procopio, N., S. Ghignone, A. Williams, A. Chamberlain, A. Mello, and M. Buckley (2018a) Metabarcoding to investigate changes in soil microbial communities within forensic burial contexts. *Forensic Science International: Genetics* 39:73–85.

Procopio, N., A. Williams, A. T. Chamberlain, and M. Buckley (2018b) Forensic proteomics for the evaluation of the post-mortem decay in bones. *Journal of Proteomics* 177:21–30.

Randall, S., C. Cartozzo, T. Simmons, J. Swall, and B. Singh (2021) Prediction of minimum postmortem submersion interval (PMSImin) based on eukaryotic community succession on skeletal remains recovered from a lentic environment. *Forensic Science International* 323:110784. DOI: 10.1016/j.forsciint.2021.110784.

Rathbun, T. A., and B. C. Rathbun (1984) Human remains recovered from a shark's stomach in South Carolina. *Journal of Forensic Sciences* 29(1):269–276.

Reed, H. B. (1958) A study of dog carcass communities in Tennessee. *American Midland Naturalist* 59(1):213–245.

Ritchie, G. T. (2005) *A Comparison of Human Decomposition in an Indoor and an Outdoor Environment*. M.A. Thesis, University of Tennessee, Knoxville, TN.

Roberts, L. G., J. R. Spencer, and G. R. Dabbs (2017) The effect of body mass on outdoor adult human decomposition. *Journal of Forensic Sciences* 62(5):1145–1150.

Rodriguez, W. C. (1997) Decomposition of buried and submerged bodies. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 459–468. CRC Press, Boca Raton, FL.

Rodriguez, W. C., and W. M. Bass (1983) Insect activity and its relationship to decay rates of human cadavers in East Tennessee. *Journal of Forensic Sciences* 28(2):423–432.

Rodriguez, W. C., and W. M. Bass (1985) Decomposition of buried bodies and methods that may aid in their location. *Journal of Forensic Sciences* 30(3):836–852.

Ross, A. H., and A. R. Hale (2018) Decomposition of juvenile-sized remains: A macro-and microscopic perspective. *Forensic Sciences Research* 3(4):310–319.

Sawafuji, R., E. Cappellini, T. Nagaoka, A. K. Fotakis, R. R. Jersie-Christensen, J. V. Olsen, K. Hirata, and S. Ueda (2017) Proteomic profiling of archaeological human bone. *Royal Society Open Science* 4(6):161004. DOI: 10.1098/rsos.161004.

Schotsmans, E. M. J., W. Van De Voorde, J. De Winne, and A. S. Wilson (2011) The impact of shallow burial on differential decomposition to the body: A temperate case study. *Forensic Science International* 206(1–3):e43–e48.

Schweitzer, M., C. L. Hill, J. M. Asara, W. S. Lane, and S. H. Pincus (2002) Identification of immunoreactive material in mammoth fossils. *Journal of Molecular Evolution* 55(6):696–705.

Shirley, N. R., R. J. Wilson, and L. M. Jantz (2011) Cadaver use at the University of Tennessee's Anthropological Research Facility. *Clinical Anatomy* 24(3):372–380.

Simmons, T. (2017) Post-mortem interval estimation: An overview of techniques. In *Taphonomy of Human Remains: Forensic Analysis of the Dead and the Depositional Environment* ed. by E, M. J. Schotsmans, N. Márquez-Grant, and S. L. Forbes, pp. 134–142. Wiley, Chichester, UK.

Simmons, T., R. E. Adlam, and C. Moffatt (2010a) Debugging decomposition data—Comparative taphonomic studies and the influence of insects and carcass size on decomposition rate. *Journal of Forensic Sciences* 55(1):8–13.

Simmons, T., P. A. Cross, R. E. Adlam, and C. Moffatt (2010b) The influence of insects on decomposition rate in buried and surface remains. *Journal of Forensic Sciences* 55(4):889–892.

Singh, B., K. J. Minick, M. S. Strickland, K. G. Wickings, T. L. Crippen, A. M. Tarone, M. E. Benbow, N. Sufrin, J. K. Tomberlin, and J. L. Pechal (2018) Temporal and spatial impact of human cadaver decomposition on soil bacterial and arthropod community structure and function. *Frontiers in Microbiology* 8:2616. DOI: 10.3389/fmicb.2017.02616.

Smith, A. C. (2014) The effects of sharp-force thoracic trauma on the rate and pattern of decomposition. *Journal of Forensic Sciences* 59(2):319–326.

Spicka, A., R. Johnson, J. Bushing, L. G. Higley, and D. O. Carter (2011) Carcass mass can influence rate of decomposition and release of ninhydrin-reactive nitrogen into gravesoil. *Forensic Science International* 209(1–3):80–85.

Stadler, S., P.-H. Stefanuto, M. Brokl, S. L. Forbes, and J.-F. Focant (2013) Characterization of volatile organic compounds from human analogue decomposition using thermal desorption coupled to comprehensive two-dimensional gas chromatography-time-of-flight mass spectrometry. *Analytical Chemistry* 85(2):998–1005.

Steadman, D. W., A. Dautartas, M. W. Kenyhercz, L. M. Jantz, A. Mundorff, and G. M. Vidoli (2018) Differential scavenging among pig, rabbit, and human subjects. *Journal of Forensic Sciences* 63(6):1684–1691.

Steadman, D. W., and H. Worne (2007) Canine scavenging of human remains in an indoor setting. *Forensic Science International* 173(1):78–82.

Stefanuto, P.-H., K. A. Perrault, R. M. Lloyd, B. Stuart, T. Rai, S. L., Forbes, and J.-F. Focant (2015) Exploring new dimensions in cadaveric decomposition odour analysis. *Analytical Methods* 7:2287–2294.

Suckling, J. K., M. K. Spradley, and K. Godde (2016) A longitudinal study on human outdoor decomposition in central Texas. *Journal of Forensic Sciences* 61(1):19–25.

Sutherland, A., J. Myburgh, M. Steyn, and P. J. Becker (2013) The effect of body size on the rate of decomposition in a temperate region of South Africa. *Forensic Science International* 231(1–3):257–262.

Swann, L. M., S. L. Forbes, and S. W. Lewis (2010) Analytical separations of mammalian decomposition products for forensic science: A review. *Analytica Chimica Acta* 682(1–2):9–22.

Tomberlin, J. K., T. L. Crippen, A. M. Tarone, B. Singh, K. Adams, Y. H. Rezenom, M. E. Benbow, M. Flores, M. Longnecker, J. L. Pechal, D. H. Russell, R. C. Beier and T. K. Wood (2012) Interkingdom responses of flies to bacteria mediated by fly physiology and bacterial quorum sensing. *Animal Behaviour* 84(6):1449–1456.

Troutman, L., C. Moffatt, and T. Simmons (2014) A preliminary examination of differential decomposition patterns in mass graves. *Journal of Forensic Sciences* 59(3):621–626.

Tsokos, O. M. (2005) Postmortem changes: Overview. In *Encyclopedia of Forensic and Legal Medicine* ed. by J. Payne-James, pp. 456–476. Elsevier, Amsterdam.

Turner-Walker, G. (2008) The chemical and microbial degradation of bones and teeth. In *Advances in Human Palaeopathology* ed. by R. Pinhasi and S. Mays, pp. 3–29. Wiley, Chichester, UK.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–87. CRC Press, Boca Raton, FL.

Ubelaker, D. H., and K. M. Zarenko (2011) Adipocere: What is known after over two centuries of research. *Forensic Science International* 208(1–3):167–172.

Varlet, V., C. Joye, S. L. Forbes, and S. Grabherr (2020) Revolution in death sciences: Body farms and taphonomics blooming. A review investigating the advantages, ethical and legal aspects in a Swiss context. *International Journal of Legal Medicine* 134(5):1875–1895.

Vass, A. A. (2011) The elusive universal post-mortem interval formula. *Forensic Science International* 204(1–3):34–40.

Vass, A. A. (2017) The use of volatile fatty acid biomarkers to estimate the post-mortem interval: Forensic analysis of the post-mortem interval. In *Taphonomy of Human Remains: Forensic Analysis of the Dead and the Depositional Environment* ed. by E. M. J. Schotsmans, N. Márquez-Grant, and S. L. Forbes, pp. 385–393. Wiley, Chichester, UK.

Vass, A. A., S.-A. Barshick, G. Sega, J. Caton, J. T. Skeen, J. C. Love, and J. A. Synstelien (2002) Decomposition chemistry of human remains: A new methodology for determining the postmortem interval. *Journal of Forensic Sciences* 47(3):542–553.

Vass, A. A., W. M. Bass, J. D. Wolt, J. E. Foss, and J. T. Ammons (1992) Time since death determinations of human cadavers using soil solution. *Journal of Forensic Sciences* 37(5):1236–1253.

Verheggen, F., K. A., Perrault, R. C. Megido, L. M. Dubois, F. Francis, E. Haubruge, S. L. Forbes, J.-F. Focant, and P.-H. Stefanuto (2017) The odor of death: An overview of current knowledge on characterization and applications. *Bioscience* 67(7):600–613.

Vidoli, G. M., D. W. Steadman, J. B. Devlin, and L. M. Jantz (2017) History and development of the first anthropology research facility, Knoxville, Tennessee. In *Taphonomy of Human Remains: Forensic Analysis of the Dead and the Depositional Environment* ed. by E. M. J. Schotsmans, N. Márquez-Grant, and S. L. Forbes, pp. 461–475. Wiley, Chichester, UK.

Voss, S. C., D. F. Cook, and I. R. Dadour (2011) Decomposition and insect succession of clothed and unclothed carcasses in Western Australia. *Forensic Science International* 211(1–3): 67–75.

Wang, Q., Y. Zhang, H. Lin, S. Zha, R. Fang, X. Wei, S. Fan, and Z. Wang (2017) Estimation of the Late postmortem interval using FTIR spectroscopy and chemometrics in human skeletal remains. *Forensic Science International* 281:113–120.

Weatherbee, C. R., J. L. Pechal, T. Stamper, and M. E. Benbow (2017) Post-colonization interval estimates using multi-species Calliphoridae larval masses and spatially distinct temperature data sets: A case study. *Insects* 8(40):1–17.

Weiss, S., D. O. Carter, J. L. Metcalf, and R. Knight (2016) Carcass mass has little influence on the structure of gravesoil microbial communities. *International Journal of Legal Medicine* 130: 253–263.

Wells, J., and L. Lamotte (2010) Estimating the postmortem interval. In *Forensic Entomology: The Utility of Arthropods in Legal Investigations* (2nd ed.) ed. by J. H. Byrd and J. L. Castner pp. 367–388. CRC Press, Boca Raton, FL.

Wescott, D. J. (2018) Recent advances in forensic anthropology: Decomposition research. *Forensic Sciences Research* 3(4):327–342.

Wescott, D. J., D. W. Steadman, N. Miller, K. Sauerwein, C. M. J. Clemmons, D. S. Gleiber, C. McDaneld, L. Meckel, and J. Bytheway (2018) Validation of the Total Body Score/Accumulated Degree-Day model at three human decomposition facilities. *Forensic Anthropology* 1(3): 143–149.

Wilson-Taylor, R. J., and A. M. Dautartas (2017) Time since death estimation and bone weathering. In *Forensic Anthropology: A Comprehensive Introduction* (2nd ed.) ed. by N. R. Langley and M. A. Tersigni-Tarrant, pp. 273–312. CRC Press, Boca Raton, FL.

Woess, C., S. H. Unterberger, C. Roider, M. Ritsch-Marte, N. Pemberger, J. Cemper-Kiesslich, P. Hatzer-Grubwieser, W. Parson, and J. D. Pallua (2017) Assessing various infrared (IR) microscopic imaging techniques for post-mortem interval evaluation of human skeletal remains. *PLoS ONE* 12(3):174552.

Wood, P. L. (2012) Lipidomics analysis of postmortem interval: Preliminary evaluation of human skeletal muscle. *Metabolomics* 3:127. DOI: 10.4172/2153-0769.1000127.

Xia, Z., B. Liu, H. Zhou, P. Lv, and J. Ma (2019) Estimation of the postmortem interval using chromatographic fingerprints of volatile organic compounds from muscle. *Journal of Forensic Science and Medicine* 5(1):13–19.

Yang, K., and X. Han (2016) Lipidomics: Techniques, applications, and outcomes related to biomedical sciences. *Trends in Biochemical Sciences* 41(11):954–969.

Zhou, C., and R. W. Byard (2010) Factors and processes causing accelerated decomposition in human cadavers—An overview. *Journal of Legal and Forensic Medicine* 18(1):6–9.

Bone Density and Bone Attrition

4

R. LEE LYMAN

Contents

Introduction

Physical anthropologists have long studied the density of human bones as a reflection of activity and other variables (references in Galloway et al. 1997; Willey et al. 1997), but seldom have they considered it as an intrinsic property of bones that has a significant mediating influence on a variety of taphonomic processes. Thus, the great majority of the literature on bone density as a taphonomically and forensically significant variable concerns nonhuman animal bones. In this chapter, I first briefly review the history of considerations of bone density in taphonomic contexts. Then, I turn to definitions of density as a generic property; this is necessary, because several different properties that more or less closely approximate the density of bone have been measured, but all have been called "density". Part of the reason that different properties have been measured is revealed by a consideration of how density has been measured in ungulate and other skeletons. Historical review of the techniques used to measure density reveals strengths and weaknesses of the several techniques, provides guidance about how density might be measured in the future, and underscores why certain density values for human skeletal parts are better than others for taphonomic/forensic purposes. Subsequent to the historical review, I turn briefly to how to quantify bone frequencies in order to determine if some skeletal parts have survived attritional processes better than other parts. This leads to a consideration of how past researchers have analytically detected density-mediated attrition in particular collections. Then I present data on the density of human bones and work through examples of analytical techniques using real data. The discussion is concluded with a few thoughts on the future study of additional intrinsic properties of bones that are taphonomically and forensically important.

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Throughout, I use the term *taphonomy* and its derivatives as a synonym for forensics; both concern answering the generic question, "Why are these particular bones here and in this condition, rather than some other bones over there in a different condition?" The term *skeletal element* is used to signify a discrete, anatomically complete unit of the skeleton such as a cervical vertebra or tibia. The term *skeletal part* is used as a generic term for a skeletal element or portion thereof, such as the distal half of a tibia or the distal condyle of a humerus. It should be kept in mind that much of the following discussion concerns the density (mass-to-volume ratio) of skeletal parts of ungulates, particularly artiodactyls such as deer (Cervidae). The basic structure of human skeletal elements and cervid skeletal elements are sufficiently similar that lessons learned from the latter should be generally applicable to the former.

History

Nearly 200 years ago, geologist William Buckland (1823:37–38) noted that a hyena quickly destroyed and devoured the proximal end of a tibia of an ox (Bovidae), then cracked the diaphysis open and consumed the exposed marrow, but "left untouched the [distal end], which contains no marrow, and is very hard". Archaeologist Karl von Adolph Morlot (1861:300) later noted that "nearly all the cartilaginous and more or less soft parts of [deer] bones [had] been subtracted" from a collection of ancient bones as a result of carnivore gnawing. Paleontologist Boyd Dawkins (1869:207) subsequently remarked that the "stone-like molars of the Mammoth would survive the destruction of all traces of the bones of the smaller mammals," and also quoted Buckland (1823) a few years later (Dawkins 1874:281–283). Finally, archaeologist Sir John Lubbock (1913:321) noted that less dense skeletal parts contained more blood, marrow, and grease and thus were more nutritious and more prone to destruction by bone-gnawing carnivores than skeletal parts of greater density. Thus, it has long been known by observant natural historians that bones of greater density—typically measured as a ratio of mass to volume—tend to survive the ravages of time better than skeletal parts of lesser density. That ancient knowledge is of an ordinal scale (i.e., it is of the greater than-less than sort), and that sufficed in the nineteenth century. It would not do in the twentieth century when quantification became a hallmark of many fields of inquiry that claimed to have the status of a science (regardless of how science might be defined beyond the necessary condition of involving empirical phenomena).

Although it was known early in the nineteenth century that the structural density of skeletal parts mediated carnivore attrition—the soft or low-density parts were destroyed, the hard or high-density parts survived gnawing—no one bothered to measure the mass-to-volume ratio of the individual parts of a skeleton and to thereby generate numerical values of density. Similarly, the fact that density seemed to mediate attritional processes did not get much attention for the first few decades of the twentieth century. Vertebrate paleontologist Dale Guthrie (1967) mentioned density as a potentially important variable that influenced the frequencies of skeletal parts of Alaskan Pleistocene mammals, but he did not measure bone density. Paleontologist and archaeologist C. K. Brain (1967) noted that modern domestic dogs (*Canis familiaris*) and humans tend to destroy skeletal parts by gnawing, preferentially consuming the softer, non-fully ossified and unfused epiphyseal ends of long bones, and neither destroying nor eating the more completely ossified and fused epiphyseal ends of long bones of domestic goats (*Capra hircus*). Two years later, he measured a kind of density (see "What is Density" section, below) of goat bones (Brain 1969). That same year, paleontologist Michael Voorhies (1969) suggested that the density of anatomically complete skeletal elements influenced their transportability by fluvial processes, but he did not measure bone density. That topic—differential fluvial transport of bones based on their density—would be taken up by Anna Behrensmeyer a few years later (1975); she measured the density of the bones of several nonhuman animal taxa for her study of Plio-Pleistocene hominid fossil and paleontological loci in eastern Africa (see also Chapter 6, this volume).

Paleontologists tended to focus on fluvial transport as mediated by the density of a skeletal part (e.g., Boaz and Behrensmeyer 1976) and the related "settling velocity" of skeletal parts (Korth 1979) [low-density parts are more readily transported by water and settle in water slower than high-density parts], whereas archaeologists focused on the damage and attrition caused by carnivore gnawing as mediated by the density of a skeletal part (e.g., Binford and Bertram 1977; Elkin 1995; Kreutzer 1992; Lyman 1984). By and large, the majority of the latter studies examined the density of ungulate bones, though eventually bones of smaller mammals (Lyman et al. 1992; Pavao and Stahl 1999), fish (Butler and Chatters 1994), and birds (e.g., Dirrigl 2001) were examined. We now have density data for nearly four dozen taxa (Table 4.1). Although some early research on bone density as a significant taphonomic property concerned human bones (Boaz and Behrensmeyer 1976), that research was not expanded upon in a taphonomic framework until the 1990s (e.g., Galloway et al. 1997; Willey et al. 1997). Because the latter research is particularly pertinent in the context of this chapter, I reserve discussion of it until later.

Table 4.1 Taxa with Bone Density Data (Chronological Order)

Taxon	Source(s)
Domestic goat (*Capra hircus*)	Brain (1969); Lam et al. (1998)
Domestic sheep (*Ovis aries*)	Behrensmeyer (1975); Binford and Bertram (1977); Lyman (1984); Ioannidou (2003); Symmons (2002, 2004, 2005)
Reedbuck (*Redunca* sp.)	Behrensmeyer (1975)
Forest hog (*Hylochocrus* sp.)	Behrensmeyer (1975)
Topi (*Damaliscus* sp.)	Behrensmeyer (1975)
Zebra (*Equus* sp.)	Behrensmeyer (1975); Lam et al. (1999)
Hippo (*Hippopotamus* sp.)	Behrensmeyer (1975)
Human (*Homo sapiens*)	Boaz and Behrensmeyer (1976); Galloway et al. (1997)
Caribou (*Rangifer tarandus*)	Binford and Bertram (1977); Lam et al. (1999)
Deer (*Odocoileus* spp.)	Lyman (1984)
Pronghorn (*Antilocapra americana*)	Lyman (1984)
Bison (*Bison bison*)	Kreutzer (1992)
Phocid seals (*Phoca* sp.)	Chambers (1992)
Marmot (*Marmota* sp.)	Lyman et al. (1992)
Cod (*Gadus* sp.)	Nicholson (1992); Smith (2008)
Chinook salmon (*Oncorhynchus tshawytscha*)	Butler and Chatters (1994)
Guanaco (*Lama guanicoe*)	Elkin (1995); Gutiérrez et al. (2010)
Vicuña (*Lama vicugna*)	Elkin (1995)
North American moose (*Alces alces*)	Hindelang and Maclean (1997)
Llama (*Lama glama*)	Stahl (1999)

(Continued)

Table 4.1 ***(Continued)*** **Taxa with Bone Density Data (Chronological Order)**

Taxon	Source(s)
Alpaca (*Lama pacos*)	Stahl (1999)
Wildebeest (*Connochaetes taurinus*)	Lam et al. (1999)
Domestic rabbit (*Oryctolagus cuniculus*)	Pavao and Stahl (1999)
Eastern cottontail (*Sylvilagus floridanus*)	Pavao and Stahl (1999)
Snowshoe hare (*Lepus canadensis*)	Pavao and Stahl (1999)
Black-tailed jackrabbit (*Lepus californicus*)	Pavao and Stahl (1999)
Turkey (*Meleagris gallopavo*)	Dirrigl (2001)
Baboon (*Papio cynocephalus*)	Pickering and Carlson (2002); Carlson and Pickering (2004)
Lesser Rhea (*Pterocnemia pennata*)	Cruz and Elkin (2003)
Pig (*Sus scrofa*)	Ioannidou (2003)
Cattle (*Bos taurus*)	Ioannidou (2003)
Domestic dog (*Canis familiaris*)	Novecosky and Popkin (2005)
Wolf (*Canis lupus*)	Novecosky and Popkin (2005)
Coyote (*Canis latrans*)	Novecosky and Popkin (2005)
Red fox (*Vulpes vulpes*)	Novecosky and Popkin (2005)
Swift fox (*Vulpes velox*)	Novecosky and Popkin (2005)
Double-crested cormorant (*Phalacrocorax auritus*)	Broughton et al. (2007)
Gadwall duck (*Anas strepera*)	Broughton et al. (2007)
Mallard (*Anas platyrhynchos*)	Broughton et al. (2007)
Pintail (*Anas acuta*)	Broughton et al. (2007)
Canada goose (*Branta canadensis*)	Broughton et al. (2007)
Common merganser (*Mergus merganser*)	Broughton et al. (2007)
Halibut (*Hippoglossus stenolepis*)	Smith (2008)
Leopard tortoise (*Stigmochelys pardalis*)	Holt et al. (2018, 2019)
Greater padloper (*Homopus femoralis*)	Holt et al. (2019)
Angulate tortoise (*Chersina angulata*)	Holt et al. (2019)
Toad (Bufonidae)	Whyte and Compton (2020)

What Is "Density"?

As noted earlier, the generic definition of density is a mass-to-volume ratio, such that

$$D = M / V$$

where:

D is the density
M is the mass
V is the volume

There are two recognized kinds of density with respect to solids that are porous. *True density* is the mass-to-volume ratio without pore space included in the measurement of volume; *bulk density* is the mass-to-volume ratio with pore space included in the measurement of volume. Thus,

$$D_t = M / V_s$$

and

$$D_b = M / V_t$$

where:

M is mass
D_t is true density
V_s is volume of the solid material only (pore space excluded)
D_b is bulk density
V_t is total volume of the substance including pore space (Lyman 1984)

The property known as *specific gravity* (SG) is also relevant here. It is a temperature-dependent measure of the ratio of the mass of a volume of a material to the mass of an equal volume of a standard substance, usually water. The equation describing SG is

$$SG = D_{te} / D_w$$

where:

D_{te} is the density of the study material at temperature *te*
D_w is the density of water

SG is the basis for the well-known relationship that at 1 atmosphere of pressure and 4°C, 1 g of distilled water has a volume of 1 cc.

Most taphonomists have not produced measures that approximate SG or true density. Instead, they have produced measures that approximate bulk density. This is useful for two reasons. First, it is appropriate to measure bulk density, because bone tissue (minus pore space) is mostly composed of hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$], which has a true density of 3.1–3.2 g/cc (Shipman 1981:25). Bone tissue itself is reported to have a density between 1.9 g/cc (Cameron et al. 1999:96) and 2.0 g/cc (Currey 1984:90). Second, from a taphonomic perspective, it is correct to measure bulk density, because it seems to be the porous structure of bone tissue that actually influences the susceptibility of the tissue to taphonomic processes. As Hill (1980) noted, the ratio of trabecular to cortical bone influences the ability of a skeletal part to withstand taphonomic processes, and Shipman (1981:25) similarly noted that the ratio of spongy to compact bone—what she referred to as the "composition" of the tissue sample, in preference to the ambiguity of "density"—influences how well a skeletal part withstands taphonomic processes. Nevertheless, throughout the remainder of this chapter, I use the term *density*, and by it I mean an approximation of bulk density. Approximation is an appropriate qualifier because of the techniques used to measure density.

How Has Density Been Measured?

Often, the term *density* is used uncritically in the taphonomy literature to describe some unspecified form of mass-to-volume relationship. This uncritical usage became clear when it was found that early measurements of the "density" of skeletal parts of confamilial taxa

Table 4.2 **Early Measurements of Bone "Density" of Ungulates (Sheep and Goat)**

Skeletal Part	Brain (1969)	Behrensmeyer (1975)	Binford (1981); Binford and Bertram (1977)
P humerus	0.58	1.26	0.78
D humerus	0.97	1.75	1.33
P radius-ulna	1.10	1.64	1.32
D radius-ulna	0.97	1.59	1.14
P femur	0.75	1.47	1.17
D femur	0.72	1.42	1.16
P tibia	0.82	1.32	1.11
D tibia	1.17	1.64	1.24

Note: P: proximal; D: distal.

tended not to correlate well with one another (Lyman 1984). As shown in Table 4.2, those early measurements were rather different even at an ordinal scale. Possible reasons for this were suggested to involve differences in the individual skeletons measured, but what quickly became apparent on close reading of the literature was the fact that the researchers involved used different measurement protocols. Brain (1969) measured what he called "specific gravity". The measurement protocol he used suggests that the property was a sort of hybrid of true and bulk density, because temperature, mass, and volume were neither rigorously controlled nor consistently measured. Behrensmeyer (1975) also measured a hybrid of true and bulk densities, because temperature and pore volume were neither rigorously controlled nor consistently measured. Binford and Bertram (1977) measured bulk density, but it was only approximate, because their efforts to include pore space volume differentially influenced measures of skeletal part volume (Lyman 1984). All of these early researchers measured the mass of a specimen (sometimes wet, sometimes dry) and used water displacement to measure the volume of a specimen. They all also apparently measured proximal and distal halves of long bones, but this was seldom explicit in the published literature. If they in fact measured such long bone halves, they were mixing varied amounts of (epiphyseal) trabecular bone tissue and (diaphyseal) laminar bone tissue in one unit. This would serve to obscure any causal relationship between a skeletal part's potential to withstand attritional processes because of its (bulk) density and the part's actual survival of density-mediated attrition.

Lyman (1984) used single-beam photon densitometry to measure the density of multiple locations (typically five or six) on most bones making up ungulate skeletons. This was an explicit acknowledgment of the fact that not only do different bones or skeletal elements of a body have different densities, but bone density (particularly, bulk density, as defined earlier) varies more or less continuously across each kind of skeletal element, much as Buckland (1823) recognized that proximal tibiae were readily destroyed whereas distal tibiae often survived carnivore ravaging. Lyman (1984) took measurements of bone density (in 1980–1981) using a (now primitive) technology that had been developed to monitor the postmenopausal loss of bone mineral in vivo among women. The single-beam photon densitometer provided a g/cm reading based on the diameter of the photon beam (1/8 in) and the distance across what Lyman (1984) termed a scan site. (The densitometer projected the photon beam through the bone by passing slowly under the specimen; a detector above determined the amount of photons that passed through the specimen. Fewer photons meant more bone mineral tissue.) The scan distance across a specimen was determined by photon beam attrition, and the machine provided that distance along with an overall g/cm measurement of bone tissue.

Lyman converted the machine-provided measurements (g/cm and scan distance) to g/cc by measuring the maximum external thickness of the skeletal part at the position of the scan; he referred to the derived measure as "volume density" (Lyman 1984). Using the third dimension measured, as Lyman did, simplified the shape of the skeletal part to a cube and also implied that the cube was internally homogenous (i.e., that bone tissue and pore space were both homogenously distributed throughout, instead of, for example, tube-like for long bone diaphyses), imparting a degree of error to the resulting measurements of density. Nevertheless, the results were sufficiently robust to explain much variation in bone survivorship in a number of collections of prehistoric ungulate remains that clearly had been influenced by destructive processes such as gnawing carnivores (in light of tooth marks on the bone specimens).

Subsequent researchers also used photon densitometry but measured bone thickness at several positions or used other techniques to derive a multidimensional estimate of volume (Elkin 1995; Kreutzer 1992; Lyman et al. 1992; Pavao and Stahl 1999; Pickering and Carlson 2002; Stahl 1999). This refined the accuracy of the measurements, but none of these researchers accounted for the medullary cavity of long bones, effectively producing measurements of density that assumed a homogenous structure in cross-section, when in fact it was heterogeneous. To resolve this issue, Lam and colleagues (Lam et al. 1998, 1999, 2003; Lam and Pearson 2005) used computed tomography, a technique that, like photon densitometry, depends on attenuation of a photon beam projected through a tissue sample. Again, the more bone mineral encountered by the photon beam, the fewer photons pass through to be detected. The significant difference between the two techniques is that while photon densitometry uses a single (or double, see the following) beam passed through a sample in one direction, computed tomography records photon beam attenuation from multiple directions and constructs a detailed cross-sectional image of the scanned sample (Cann 1988; see also Novecosky and Popkin 2005). Cautious use of photon densitometry values can, nevertheless, provide insight into whether a collection of bones has undergone density-mediated attritional taphonomic processes (Carlson and Pickering 2004). Some researchers have used dual-energy x-ray absorptiometry (Ioannidou 2003; Pickering and Carlson 2002). Again, the most serious weakness attending this technique is measurement of the volume of the specimen under study, and again, some find it less satisfactory than photon densitometry (Symmons 2004, 2005).

Bone Frequencies and Survivorship

How does one determine frequencies of skeletal parts if one is interested in detecting density-mediated attrition? Note that I said "determine frequencies" rather than "tally frequencies". A tally is simply a summed enumeration of each individual part. However, if one wishes to know if one skeletal part is better represented (i.e., survived taphonomic attritional processes better) than another part, then simply saying there are more ribs than thoracic vertebrae will not do. This is so because there are twice as many ribs (lefts plus rights) as there are thoracic vertebrae per mammal skeleton. The quantitative protocol typically followed takes advantage of the fact that different bone types (ignoring left-right distinctions) have different frequencies in a body (one cranium, seven cervical vertebrae, two humeri etc.), and it also takes advantage of the fact that we know how many of each bone type are necessary to make up one complete skeleton. Therefore, simplistically, three humeri represent 1.5 bodies, and if we know that three bodies were at one time present, then the %survivorship of humeri is the equivalent of 50, even if all three humeri are left elements. The implicit assumption is that all skeletal parts of a kind (e.g., humeri) have equivalent survival potential regardless of anatomical side. Similarly, vertebrate taphonomists typically assume that all vertebrae of each category (cervical, thoracic, lumbar, sacral, and caudal) have equivalent survival potential, but different categories have different survival potential. The only exception to this assumption is that C1 (atlas) and C2 (axis) are often treated individually.

It is critical to make the quantitative protocol clear. First, one determines categories of skeletal parts for tallying; these can be anatomically complete skeletal elements such as ribs, femora, and tibiae, but often long bones are tallied by proximal and distal halves, such as proximal femora and distal tibiae. Finer distinctions of portions of individual skeletal elements can also be made (as in the examples on human remains presented later). Then, one may tally up the number of identified specimens (NISP) per category of skeletal part. If a category is the distal half of the tibia, then any specimen that represents in whole or in part that category represents a tally of 1 for that category. The analyst, however, must determine the minimum number of skeletal parts per category, typically in zooarchaeology labeled the MNE or minimum number of elements (Lyman 1994a,b, 2008). The MNE is a minimum, because it represents the smallest possible number of skeletal parts necessary to account for the specimens or NISP of a skeletal part category. For example, assume that we have seven fragments (NISP) of proximal left tibiae. Two (A and B) of those fragments represent the proximal articulation and refit one another (like a jigsaw puzzle), a third specimen (C) represents a portion of the diaphysis that does not anatomically overlap A or B, and the other four specimens (D, E, F, G) are all anatomically complete proximal halves of left tibiae. These seven (= NISP) specimens represent a minimum of five (= MNE) proximal left tibiae. It is a minimum, because specimens A and B represent one proximal tibia that could anatomically overlap (be redundant with) specimens D, E, F, and G. Specimen C, however, overlaps specimens D, E, F, and G, but does not overlap specimens A and B and thus *could* be part of the same particular element as A and B. Thus, the true number of proximal left tibiae could be five, or it could be six; by convention (originating in paleontology and transferred to zooarchaeology [Grayson 1984; Lyman 2008]), the minimum is used for analysis.

The preceding concerns the determination of NISP and MNE. What about survivorship? If there is an MNE of four proximal right tibiae along with the MNE of five left tibiae described in the preceding paragraph, then the minimum number of animal units (MAU) or survivorship (the two are mathematically identical [Lyman 1994a]) is 4.5 (=[4+5]/2). MAU is derived by dividing the total MNE for a skeletal part category by the number of times that category occurs in a single complete skeleton. The division norms (or normalizes) the MNE counts to the standard of a carcass (see Lyman [2008] for extended discussion).

Single-element and multi-element skeletal portions are treated in the same way. Say, for example, fragments of the skull represent an MNE of four skulls; divide that MNE by 1 to determine the MAU of skulls. On the other hand, let us say that we have 45 NISP of ribs, and those specimens represent an MNE of 20 ribs. Divide 20 by 26 (the number of left + right ribs in a single ungulate) to derive a value of 0.769 MAU (or survivorship) of ribs. Norming the MNE values to MAU values is unnecessary if, for example, only paired long bones are considered, because in that case, all MNE values would be divided by 2.

Once MAU values are available for all skeletal categories (parts such as distal humeri and multi-element portions such as thoracic vertebrae), those values can be transformed to %survivorship (also known as %MAU) values. This transformation is done by individually dividing the MAU value for each skeletal part by the maximum observed MAU in the assemblage. For example, if the maximum MAU is for distal humeri and it is 20, then divide the MAU of all skeletal parts and portions, including distal humeri, by 20 (and multiply the result by 100) to determine the %survivorship. A maximum MAU of 20 distal humeri in a collection indicates there should be (we would expect) an MAU of 20 proximal humeri (or 40 MNE), 140 cervical vertebrae, 10 skulls, etc., if all parts of every skeleton were present and had survived destructive taphonomic processes equally. If the observed values of those skeletal portions are less than the expected values, then some parts are not represented in their expected total frequencies for any of a myriad of reasons, including the fact that perhaps they did not survive density-mediated attritional processes because they were of relatively low density. The variable %survivorship and its mathematical equivalent %MAU are useful for the comparison of samples of disparate sizes to facilitate detection of similarities and differences between abundances of skeletal parts in two or more collections. They need not be calculated if only one collection is examined. As the following examples indicate, tallies of MNE suffice when all categories of skeletal parts occur with equal frequency in a skeleton (e.g., humeri, tibia, and femora); determine MAU if the included kinds of skeletal parts vary in frequency in a carcass (e.g., cervical vertebrae or ribs).

How to Determine Attrition

Brain (1967, 1969) noted two things about the relationship between the density and what he referred to as the “survival” of skeletal parts in a collection of domestic goat bones gnawed by dogs and humans. First, unfused ends of goat long bones were infrequent relative to fused ends in the collection of more than 2000 NISP, where a *specimen* is a skeletal element (an anatomically complete bone) or a fragment thereof (Grayson 1984; Lyman 2008). Second, what Brain termed the “specific gravity” of the long bone ends that fused ontogenetically early in life tended to be greater than the SG of ends that fused ontogenetically late in life (Brain 1969). He showed this in several ways; one was a table of the data, reproduced here as Table 4.3, and another involved a graphical representation of the relationship, reproduced here in modified form as Figure 4.1. Brain (1969) also constructed histograms of the frequencies of skeletal parts of goats, ordering the parts from most frequent to least frequent, noting that parts with larger SG values tended to be more frequent than those with smaller SG values (see also Brain 1976). Brain (1969, 1976) did not calculate correlation coefficients between any of the pairs of variables, but his interpretation of the relationships between the variable pairs was spot on. Spearman’s rank-order correlation coefficient between the SG values he determined and survivorship is positive and significant (*rho* = 0.874, $p = 0.007$), and while the correlation between age at fusion and survivorship is not significant, it is an inverse relationship (*rho* = −0.599, $p = 0.13$), just as Brain suspected.

Binford and Bertram (1977) presented data in a plethora of tables and figures that showed the frequencies of skeletal parts in several collections of ungulate bones. Binford and

Table 4.3 **Observations on the Relationship between Ontogenetic Age When Epiphysis Fuses, Specific Gravity, and Bone Frequencies (Normed to %Survival)**

Skeletal Part	%Survival	Specific Gravity	Age at Fusion (months)
P humerus	0.0	0.58	17
D humerus	64.0	0.97	4
P radius-ulna	50.8	1.10	4
D radius-ulna	17.2	0.97	21
P femur	14.1	0.75	18
D femur	7.0	0.72	20
P tibia	10.1	0.82	25
D tibia	56.3	1.17	15

Source: Brain (1969).

Note: P: proximal; D: distal.

Bertram (1977: Figure 3.16) clearly illustrated, in the form of a bivariate scatter plot, the direct relationship between the surviving frequencies of skeletal parts and bone density. A version of that figure is shown here in Figure 4.2. Binford computed a polynomial regression to describe the relationship between the two variables; the simple linear correlation coefficient was significant ($r = 0.863$, $p < 0.0001$), as was the rank-order correlation coefficient ($rho = 0.907$, $p < 0.0001$). Binford did not later use this sort of bivariate plot; instead he (Binford 1981:219) developed a different type of graph that could quickly provide an indication of

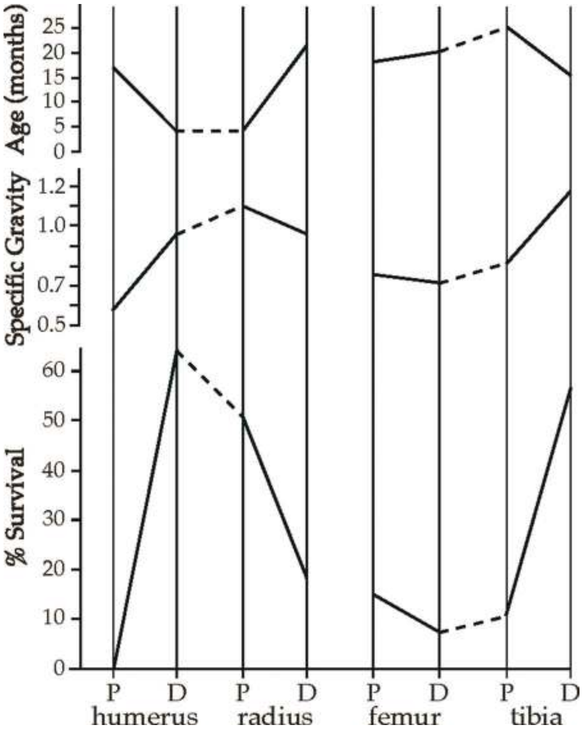

Figure 4.1 Brain's illustration of the relationship between the age (in months) when an epiphysis fused, the specific gravity of a skeletal part, and the %survival of skeletal parts in a collection of goat bones (After Brain 1969, 1976.)

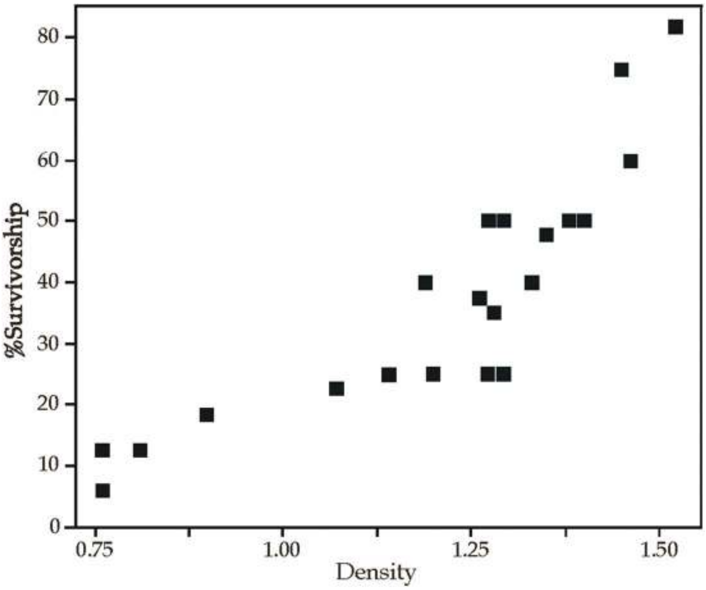

Figure 4.2 Binford's bivariate scatter plot of the density of caribou (*Rangifer tarandus*) skeletal parts and the frequency of skeletal parts in a collection of caribou bones that had been gnawed by dogs (After Binford and Bertram 1977.)

density-mediated destruction. Referred to as "bone-destruction graphs" (Lyman 1994c:401), these graphs are rapidly constructed, because the analyst can include as many or as few data points as desired. Each plotted point requires two calculations—the frequency of the high-density end of a long bone and the frequency of the low-density end of that long bone. Included frequencies are normalized to a scale of 0–100. The quick way to accomplish this task when the skeletal remains are from artiodactyls is to determine frequencies of relatively low-density proximal humeri, proximal tibiae, and distal radii, and frequencies of relatively high-density distal humeri, distal tibiae, and proximal radii. Those frequencies are presented in Table 4.3 for Brain's (1969) data and are plotted on the destruction graph in Figure 4.3. That plot suggests, not surprisingly, that the represented set of goat bones has undergone some degree of density-mediated attrition. If the destruction graph produces an ambiguous result, then all skeletal parts for which frequency data and density data are available can be plotted in a bivariate scatter plot like that in Figure 4.2 and a correlation coefficient calculated. Spearman's rank-order correlation coefficient (*rho*) (as opposed to Pearson's correlation coefficient, *r*) is recommended, because: (a) skeletal part abundance data tend to be at best ordinal scale (Grayson 1984; Lyman 2008), and (b) differences in density of skeletal parts are likely at best ordinal scale as well given variation in individual age, sex, genotype, nutrition, and health status, variables known to influence bone density (Lyman 1984).

Binford (1984:87) used a single destruction graph in a later analysis. Lyman (1984) merely listed correlation coefficients between %survivorship and bone density values under the presumption that a statistically significant (positive) coefficient indicated density-mediated attrition had taken place. He continued that pattern in later analyses (e.g., Lyman 1993, 1994a). Some followed this analytical strategy (e.g., Ioannidou 2003; Kreutzer 1992; Pavao and Stahl 1999). Others published not only correlation coefficients but also bivariate scatter plots that showed the relationship between the density and the frequency

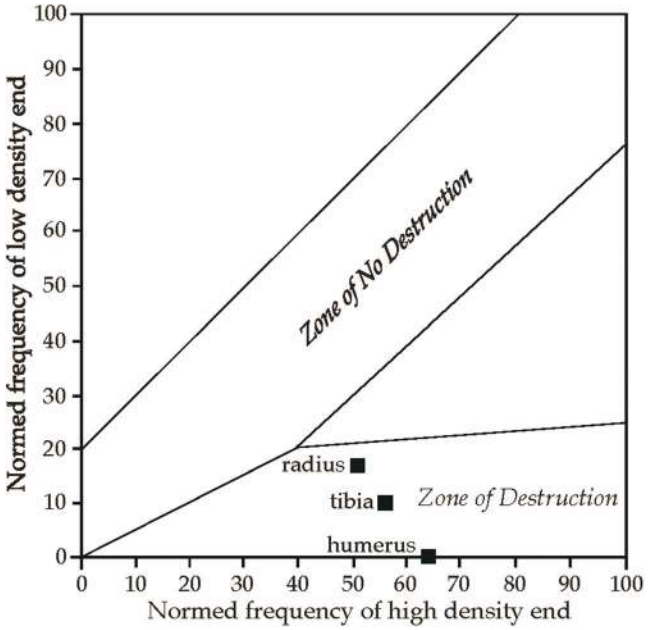

Figure 4.3 Binford's destruction graph with frequencies of proximal and distal humeri, radii, and tibiae of goats in Brain's (1969) sample. Data from Table 4.1. (Graph design from Binford 1981.)

of multiple kinds of skeletal parts (e.g., Bartram and Marean 1999; Cruz and Elkin 2003; Dirrigl 2001; Klein 1989; Pickering and Carlson 2002). Most recently, Bever (2004) showed that identical correlation coefficients could be obtained from quite different relationships between frequencies of skeletal parts and their respective densities. He therefore suggested that the analyst both build a scatter plot and calculate a correlation coefficient. That way, one could determine both what kind of relationship existed (by the form of the scatter of points) and if that relationship was significant (by the correlation coefficient). Today, taphonomists would argue that the analyst also should examine individual bone specimens for evidence of density-mediated attritional agents such as carnivore gnawing damage to assist with interpreting what the frequencies of skeletal parts actually reflect with respect to their taphonomic history.

Human Bone Density

As indicated earlier, there are limited data on the density of human skeletal parts determined for the purposes of taphonomy or forensics. Boaz and Behrensmeyer (1976) produced measurements of human skeletal parts that seem to approximate bulk density. They found a significant inverse correlation ($r = -0.63$, $p < 0.001$) between the bulk density of a skeletal part and its velocity of transport in flowing water. That is, parts of high density moved slowly, whereas parts of low density moved more rapidly. Boaz and Behrensmeyer's (1976) density data were, however, based on unprovenienced prehistoric human remains that were poor proxies for fresh bone, the remains were few in number, and density was estimated based on volumes derived from water displacement and was done in such a manner as to be likely not replicable. To generate what are arguably the most sophisticated data thus far published on the density of human skeletal parts, Galloway et al. (1997) used single-beam photon absorptiometry and measured multiple loci on the six major long bones of multiple modern human skeletons. The majority of the bone portions scanned with the photon densitometer were located at a set percentage of an element's total length from the distal end; these are shown in Figure 4.4. To produce a measure of density

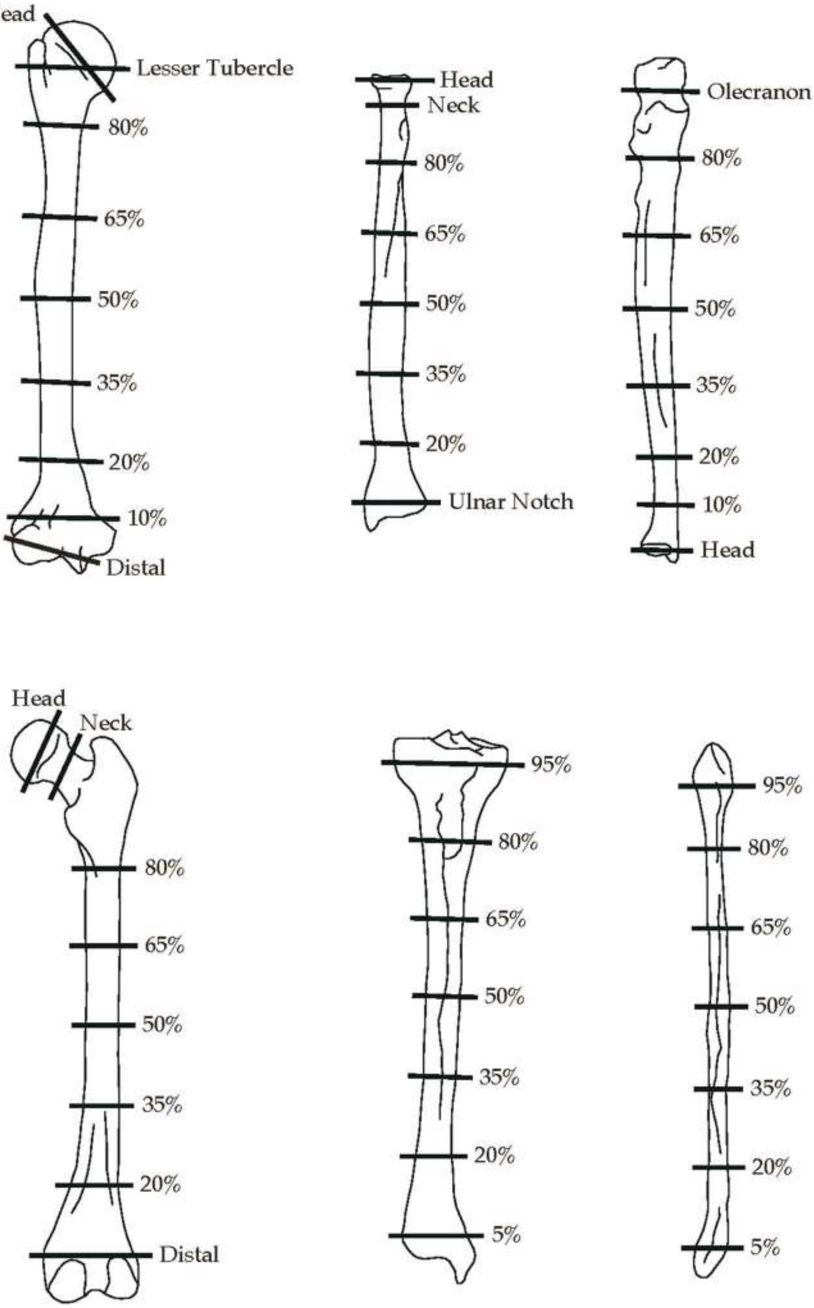

Figure 4.4 Scan site locations on human long bones where density was measured. (Redrawn from Galloway et al. 1997.)

that took into account the cross-section shape of the bone at each scan site, Galloway et al. (1997) measured the circumference of each scan site, divided that value by 3.14 (π) to obtain an approximate diameter of the scan site, and then divided the bone mineral content of each scan site (provided by the densitometer) by the diameter. They found that this measure of density, which they termed bone mineral density by circumference (BMDc), provided a good predictor of bone survivorship in the prehistoric collection of human remains that they examined. It was in fact better than the value of density calculated following Lyman's (1984) protocol, although BMDc still assumes a uniform structure or amount of bone tissue throughout the scan site—the problem later addressed by computed tomography (Lam et al. 2003; Lam and Pearson 2005).

Galloway et al. (1997) and Willey et al. (1997) originally presented their bone density data for 22 male and 8 female, left and right elements, of adult Caucasians. They provided me with their original raw data per skeleton, and following the protocol of taphonomists who have examined nonhuman skeletons, I calculated mean BMDc values for each scan site on the six limb/long bones regardless of side or sex (Table 4.4). Galloway et al. (1997)

Table 4.4 Summary Density Data for Human Long Bones by Scan Site

Scan Site	Mean ± SD	NSP Measured
Humerus head	0.832 ± 0.177	54
Humerus tubercle	0.704 ± 0.176	54
Humerus 80%	0.867 ± 0.182	56
Humerus 65%	1.107 ± 0.277	56
Humerus 50%	1.228 ± 0.328	56
Humerus 35%	1.246 ± 0.307	56
Humerus 20%	1.270 ± 0.297	56
Humerus 10%	0.925 ± 0.251	56
Humerus distal	0.847 ± 0.216	56
Radius head	0.717 ± 0.229	53
Radius neck	0.581 ± 0.136	58
Radius 80%	0.780 ± 0.195	58
Radius 65%	0.849 ± 0.180	58
Radius 50%	0.910 ± 0.177	58
Radius 35%	0.895 ± 0.176	58
Radius 20%	0.749 ± 0.148	58
Radius ulnar notch	0.561 ± 0.137	55
Ulna olecranon	0.704 ± 0.192	55
Ulna 80%	0.975 ± 0.214	55
Ulna 65%	0.996 ± 0.181	55
Ulna 50%	0.884 ± 0.212	55
Ulna 35%	0.833 ± 0.164	55
Ulna 20%	0.658 ± 0.142	55
Ulna 10%	0.420 ± 0.103	54
Ulnar head	0.417 ± 0.092	54
Femur head	1.024 ± 0.337	50
Femur neck	0.870 ± 0.284	51
Femur 80%	1.617 ± 0.379	50
Femur 65%	1.810 ± 0.319	50

(Continued)

Table 4.4 ***(Continued)*** **Summary Density Data for Human Long Bones by Scan Site**

Scan Site	Mean ± SD	NSP Measured
Femur 50%	1.717 ± 0.314	50
Femur 35%	1.512 ± 0.320	49
Femur 20%	1.171 ± 0.270	50
Femur distal	0.999 ± 0.298	48
Tibia 95%	0.811 ± 0.286	45
Tibia 80%	0.982 ± 0.343	46
Tibia 65%	1.226 ± 0.371	46
Tibia 50%	1.320 ± 0.373	46
Tibia 35%	1.272 ± 0.359	46
Tibia 20%	0.940 ± 0.341	46
Tibia 5%	0.761 ± 0.282	42
Fibula 95%	0.362 ± 0.117	44
Fibula 80%	0.591 ± 0.150	50
Fibula 65%	0.717 ± 0.183	50
Fibula 50%	0.735 ± 0.191	50
Fibula 35%	0.748 ± 0.160	50
Fibula 20%	0.821 ± 0.107	40
Fibula 5%	0.561 ± 0.171	47

Note: All Caucasian adults (22 Males, 8 Females); both lefts and rights included.

found that scan sites of right elements displayed greater densities than left elements within each sex, that scan sites of male elements displayed greater densities than female elements, and that scan sites of African American skeletons were denser than those in Caucasian skeletons. However, overall, correlations between scan sites across sides, sexes, and ancestries were relatively strong and statistically significant. This suggests that we can use Caucasian skeletons (the most frequent skeletal type measured) as a general model indicating the density-mediated survival potential of one skeletal part relative to another, regardless of the side, sex, or race of those parts. That is, if the right distal humerus is denser than the right proximal humerus among male Caucasians, we can assume that the left distal humerus is denser than the left proximal humerus among female African Americans and other ancestry-sex categories as well. How well, then, do the density data in Table 4.4 explain frequencies of skeletal parts in a collection of imperfectly preserved human skeletons?

Unfortunately, few studies of large collections of human skeletal remains provide frequencies of skeletal parts in a form conducive to analysis (e.g., Turner and Turner 1999; White 1992). Willey et al. (1997) provided just such data for Crow Creek, a fourteenth-century collection of remains of about 500 individual American Indians who were massacred. The archaeological site is a prehistoric village located in south-central South Dakota. The MNE values of all but two scan sites shown in Figure 4.4 are provided by Willey et al. (1997) and listed in Table 4.5. There is no need to calculate MAU values in this case, because all tallied skeletal parts (scan sites) would be divided by 2. There is also no need to norm the frequency values to %MAU (or %MNE for that matter), because this need only be done when two assemblages of widely disparate sizes are compared (see “Bone Frequencies and Survivorship” section, above).

Following the precedents set in studies of density-mediated attrition among ungulate remains, there are several kinds of analysis that can be performed with the Crow Creek

Table 4.5 Frequency (MNE) of Each Scan Site among American Indian Long Bones at the Crow Creek Site

Scan Site	MNE	Scan Site	MNE
Humerus head & tubercle	170	Femur head & neck	496
Humerus 80%	288.5	Femur 80%	569.5
Humerus 65%	310.5	Femur 65%	555
Humerus 50%	322	Femur 50%	554.5
Humerus 35%	329.5	Femur 35%	545.5
Humerus 20%	340.5	Femur 20%	522
Humerus 10%	150.5	Femur distal	311
Humerus distal	250	Tibia 95%	288.5
Radius head	145	Tibia 80%	405
Radius neck	150.5	Tibia 65%	427.5
Radius 80%	175.5	Tibia 50%	432
Radius 65%	176	Tibia 35%	425
Radius 50%	163	Tibia 20%	409.5
Radius 35%	163	Tibia 5%	342.5
Radius 20%	135	Fibula 95%	165
Radius ulnar notch	53.5	Fibula 80%	214.5
Ulna olecranon	160.5	Fibula 65%	224.5
Ulna 80%	201	Fibula 50%	236
Ulna 65%	206	Fibula 35%	229
Ulna 50%	183	Fibula 20%	210.5
Ulna 35%	183	Fibula 5%	155
Ulna 20%	138		
Ulna 10%	57.5		
Ulnar head	38		

Source: Willey et al. (1997).

data. As indicated earlier, a quick way to determine if density-mediated attrition has affected an assemblage would be to construct a destruction graph like that in Figure 4.3. To construct such a graph for the Crow Creek remains, I chose one high-density scan site and one low-density scan site for each long bone in Figure 4.4 with the exception of the fibula. Frequencies of each were normed to the scan site with the greatest value in order to plot the data on the destruction graph. For illustrative purposes, the data used are summarized in Table 4.6, and the resulting destruction graph is shown in Figure 4.5. That graph suggests that indeed the Crow Creek remains have undergone some density-mediated attrition, though the results are more ambiguous than one might hope. The graph suggests the radius and ulna have undergone density-mediated destruction, though this may be a function of the small sample size for these elements. The humerus and femur may have undergone minor destruction, and apparently the tibia did not undergo any significant destruction. In just such a case, one should turn to a different technique for assessing whether the attrition of a collection was density-mediated or not.

Another way to determine if the Crow Creek materials have been subjected to density-mediated attrition is to construct a scatter plot of the BMDc of each of the 45 scan sites (the independent variable, on the x axis) against its MNE frequency (the dependent variable, on the y axis). Just such a plot is shown in Figure 4.6. The scatter plot implies the

Table 4.6 **Frequency (MNE) of Scan Sites Selected for the Construction of a Destruction Graph**

Scan Site	MNE	Normed (%)MNE
Humerus head	170	29.8
Humerus 20%	340.5	59.8
Radius 80%	175.5	30.8
Radius ulnar notch	53.5	9.4
Ulna 80%	201	35.3
Ulna head	38	6.7
Femur 80%	569.5	100.0
Femur distal	311	54.6
Tibia 65%	427.5	75.1
Tibia 5%	342.5	60.1

Note: Normed (%)MNE = [MNE/569.5]100.

two variables are correlated, the relationship is direct and linear, and therefore the Crow Creek remains have undergone density-mediated attrition of some sort, though the identity of the responsible taphonomic agent is unclear. Finally, calculation of a rank-order correlation coefficient (Spearman's *rho* = 0.806, $p < 0.0001$) and overlaying the simple best-fit regression line confirm our subjective interpretation based on the scatter plot of

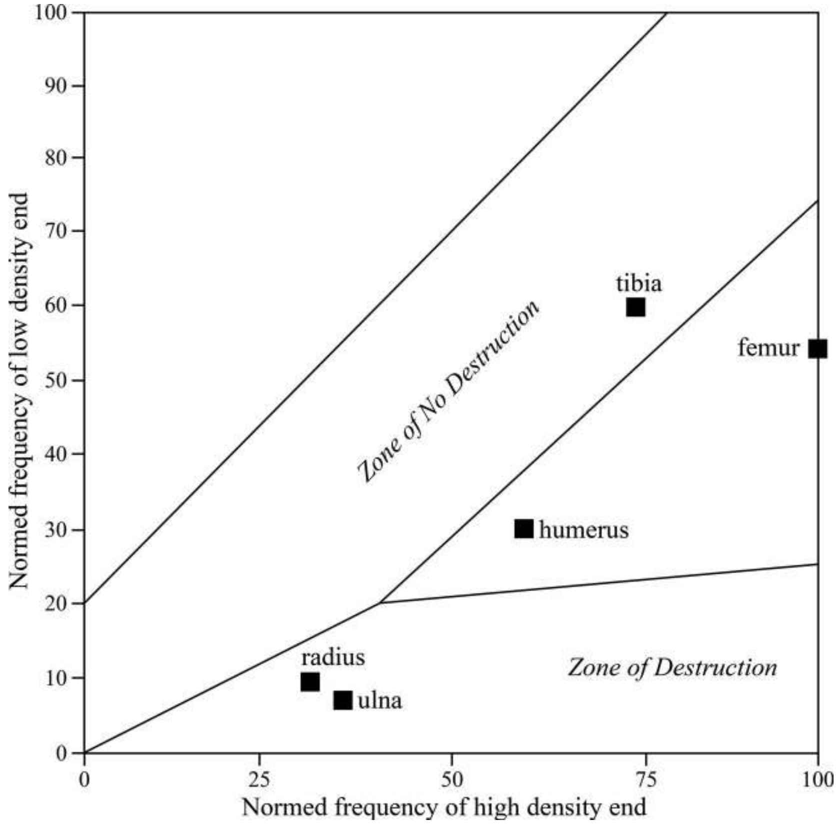

Figure 4.5 Destruction graph for the American Indian remains from Crow Creek. Data from Table 4.6.

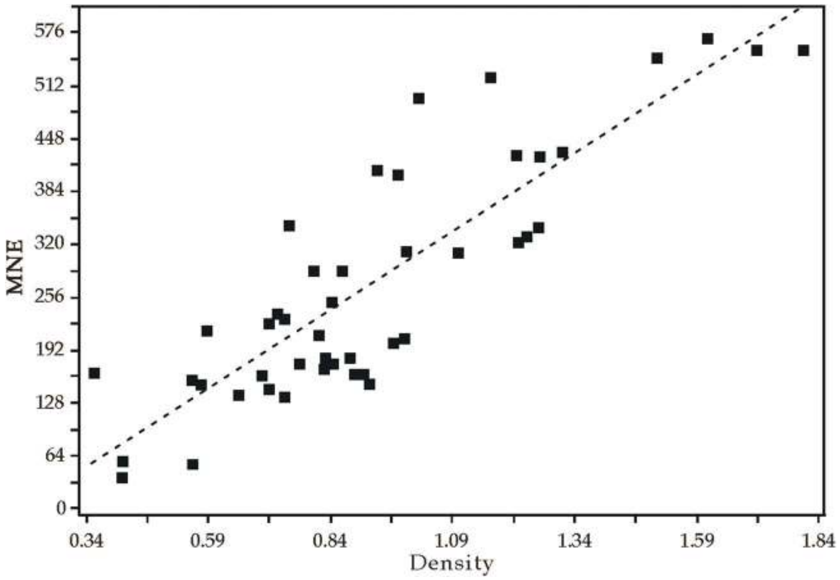

Figure 4.6 Bivariate scatter plot of the density of 45 scan sites on human long bones against MNE frequencies of American Indian remains from Crow Creek. Data from Table 4.5.

the relationship between the two variables. As Willey et al. (1997) reported, given gnawing damage to some of the human remains, it is likely that consumption by scavenging carnivores is the responsible taphonomic process. Although it is beyond the scope of this discussion, I suspect differential recovery, in particular the failure to recover small pieces such as the distal ulna (ulnar head) and parts of the fibula, has contributed to the observed frequencies of skeletal parts.

Discussion

There are two interrelated reasons to be concerned about variability in the density of skeletal parts, regardless of the taxon. First, many taphonomic processes—carnivore attrition, chemical alteration, fluvial transport, settling in fluid media, and the like—are mediated by the density of a skeletal part (Lyman 1994c). Second, we know of what a complete skeleton of an individual is composed—for a mammal, a cranium, seven cervical vertebrae, a left scapula, right scapula, left humerus, right humerus, left radius, etc.—and thus we can immediately determine if we have something less than (or more than) a single (or multiple) complete skeleton(s) lying on the laboratory table. Together, these two facts mean that we can begin to surmise the preservational condition of a collection of skeletal remains based on its inventory. If certain parts are missing, for example, those known to be of low structural density, then we have immediate insight into the general taphonomic history of the materials comprising the collection. It cannot be overemphasized, however, that the discovery of a significant statistical correlation between skeletal part frequencies and part density does not indicate which particular density-mediated taphonomic process (or even if there was one) influenced the collection. Inference of the taphonomic agent(s) involved requires other sorts of observations, such as if (and how many) specimens display evidence of carnivore gnawing (e.g., Fernández-Jalvo and Andrews 2016), if specimens appear abraded (e.g., Fernández-Jalvo and Andrews 2003), if specimens have a corroded appearance (e.g., Fernández-Jalvo et al. 2014), or the like.

Density as a mass-to-volume ratio is the single most-studied intrinsic property of skeletal tissue not only because it is directly related to physiological health and thus susceptibility to bone fracture, but also because of its influence on bone preservation. There are other, perhaps equally important intrinsic properties of skeletal tissues that have received much less attention from taphonomists, paleontologists, and forensic scientists (hence the "perhaps equally important" qualification). These include bone size, bone shape, and bone porosity. Paleontologists demonstrated bone shape influences various taphonomic processes (Frostick and Reid 1983), and zooarchaeologists found bone shape and bone size influence survivorship (Darwent and Lyman 2002). Despite recognition of the probable taphonomic significance of these intrinsic properties 30+ years ago, surprisingly little is known about how influential they are on taphonomic processes.

Porosity is related to bulk density, and given the demonstrable importance of bulk density to taphonomy, the difficulty of measuring bulk density documented in this chapter, and the mediating influence of porosity on diagenetic (post-burial taphonomic) processes, Lyman (1984) wondered if measuring bone porosity might provide a better predictor of skeletal part preservational quality, including survivorship, than bulk density. Some progress has been made in measuring porosity (e.g., Smith et al. 2008 and references therein), but thus far the property has not been applied very often in an explanatory role in either forensics or taphonomy. So, as far as I know, the porosity of human skeletal parts has not been measured.

Golda (2015) investigated the influence of bone density, bone size, and bone shape on skeletal part survivorship among remains of US-Mexico border-crossers. She found mean maximum size (~length) of anatomically complete skeletal elements to be positively correlated with survivorship ($rho = 0.458$, $p < 0.05$), as were Galloway et al.'s (1997) measures of bone density ($rho = 0.476$, $p < 0.05$). Importantly, Golda (2015) also found survivorship to vary based on four basic shapes developed by sedimentologists to study the influence of sediment particle shape on fluvial transport, settling, etc. (Krumbein 1941; Zingg 1935). Shape of an object is determined by: (a) measuring its three perpendicular axes, not unlike length, width, and thickness; (b) calculating the axial ratios of width-to-length and thickness-to-width; and (c) plotting those ratios as in Figure 4.7. Golda (2015:80) determined the shape classes of the major elements of the human skeleton following this protocol (Figure 4.7). Future work should explore further the influence of bone shape on survivorship and preservational quality.

Biological interpretations of collections of human remains, whether archaeologically or forensically derived, demand knowledge of which skeletal parts are missing. For example, interpretations of ontogenetic age at death of individuals could be biased if no dentitions are available. Knowing *which* particular parts are missing indicates what sorts of questions can be answered with the materials at hand. Knowing *why* particular skeletal parts are missing provides indications of taphonomic history and forensic history, and contributes to building warranting arguments for answering some kinds of questions but not others. The universal influence of the density of a skeletal part as an intrinsic property of skeletal parts that mediates many taphonomic processes makes it indispensable to bioarchaeological, zooarchaeological, and forensic research.

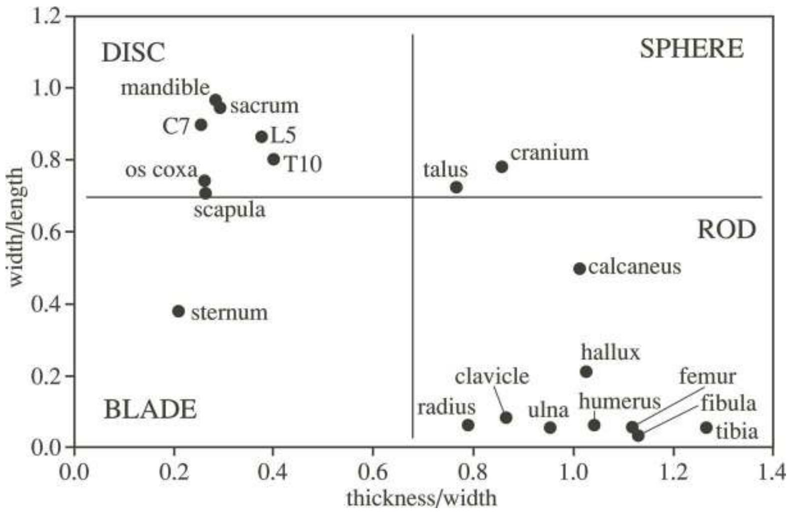

Figure 4.7 Shape classification of major elements of the human skeleton. (After Golda 2015:80.)

Conclusion (or on the Future)

Brain (1967) originally noted that long bones—both the diaphyses and the epiphyses—with unfused epiphyses tend not to survive ravaging by bone-gnawing carnivores as well as long bones with fused epiphyses. This has been thought to relate to the fact that ossification and calcification increase with ontogenetic age; that is, density increases with increased age (at least to some middle age, after which it may decrease). Recent research on domestic sheep (*Ovis aries*) suggests that although unfused long bone ends tend to be less dense than fused ends, the relationship is neither rigid nor consistent across the skeleton (Symmons 2005). Further, no statistically significant relationship was found between increasing age and density (Symmons 2005). However, work with domestic pig (*Sus scrofa*) bones indicates that skeletal parts of younger individuals are less dense than those of older individuals (Ioannidou 2003). Results for South American camelids also suggest, but do not conclusively demonstrate, that bones of younger individuals are more prone to destruction than bones of older individuals (Izeta 2005). It seems, then, that the nature of the relationship between ontogenetic age and density of skeletal parts will need to be determined for each population of each species.

The density data gathered by Galloway et al. (1997) and Willey et al. (1997) and summarized in Table 4.5 are presently the best available on human bones. This is so for two reasons. First, the data in Table 4.5 involve averages; each value incorporates sexual and some ontogenetic or age variation (though all were adults in the sense of having fused epiphyses) within a single ancestral population. Second, multiple scan sites per skeletal element (seven or eight per element) are included, giving statistical power to any test using those data to detect density-mediated attrition. Only one other study of human bone has used photon densitometry to derive measures of density (Suby and Guichón 2004), but they measured only one skeleton and three or fewer scan sites per skeletal element. Their data for limb bones correlate well with those in Table 4.5 (Pearson's $r = 0.839$, $p < 0.0001$), suggesting that the data on the density of vertebrae, the clavicle, scapula, and major tarsals presented by Suby and Guichón (2004) might be useful. I do not present them here, however, because Suby and Guichón (2004) measured an archaeological skeleton, and some of their measurements concern whole bones rather than particular scan sites.

The data in Table 4.5 are sufficient to provide significant insight to the taphonomic history of a collection and whether that collection underwent density-mediated attrition or not, but more research is needed on racial and sexual variation, as well as the aforementioned ontogenetic variation in the density of skeletal parts. In addition, we need data on bone density measured via computed tomography or a similar technique in order to control fully for the cross-section morphology and structure of each scan site. Together, detailed data on population, sexual, ontogenetic, and cross-sectional structure will likely increase the correlation between density and survivorship. Such data may help explain some of the residual variation when a correlation coefficient between density and frequency is < 1.0. We also need data for skeletal parts other than long bones, including vertebrae, crania, carpals, tarsals, phalanges, etc. Finally, even when we have much more complete data, it is important to keep in mind that modern taphonomic research must include multivariate analysis. Density is only one intrinsic property of skeletal elements with taphonomic and forensic significance. Others include bone size and shape (e.g., Darwent and Lyman 2002), and porosity (e.g., Lyman 1984), and associated soft tissue (Binford 1978). The data in Table 4.5 and Figure 4.7 provide but a starting point for a thorough taphonomic analysis of human bone survivorship and its meaning.

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Many thanks to P. Willey and Alison Galloway for allowing me to use their density data in new analyses and to publish it in a new form. Thanks to Stephanie Golda for permission to use what in this chapter is Figure 4.7. Cynthia Irsik was more than helpful (and saved me a lot of hours) with translating an archaic and quite large data file into something that I could use.

References

Bartram, L. E., Jr. and C. W. Marean (1999) Explaining the "Klasies Pattern": Kua ethnoarchaeology, the Die Kelders Middle Stone Age archaeofauna, long bone fragmentation and carnivore ravaging. *Journal of Archaeological Science* 26(1):9–29.

Behrensmeyer, A. K. (1975) The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages east of Lake Rudolf, Kenya. *Bulletin of the Museum of Comparative Zoology* 146:473–578.

Bever, J. E. (2004) Identifying necessity and sufficiency relationships in skeletal-part representation using fuzzy-set theory. *American Antiquity* 69(1):131–140.

Binford, L. R. (1978) *Nunamiut Ethnoarchaeology*. Academic Press, New York.

Binford, L. R. (1981) *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Binford, L. R. (1984) *Faunal Remains from Klasies River Mouth*. Academic Press, Orlando, FL.

Binford, L. R. and J. B. Bertram (1977) Bone frequencies and attritional processes. In *For Theory Building in Archaeology* ed. by L. R. Binford, pp. 77–153. Academic Press, New York.

Boaz, N. J. and A. K. Behrensmeyer (1976) Hominid taphonomy: Transport of human skeletal parts in an artificial fluviatile environment. *American Journal of Physical Anthropology* 45(1):53–60.

Brain, C. K. (1967) Hottentot food remains and their bearing on the interpretation of fossil bone assemblages. *Scientific Papers of the Namib Desert Research Station* 32:1–7.

Brain, C. K. (1969) The contribution of the Namib Desert Hottentots to and understanding of Australopithecine bone accumulations. *Scientific Papers of the Namib Desert Research Station* 39:13–22.

Brain, C. K. (1976) Some principles in the interpretation of bone accumulations associated with man. In *Human Origins: Louis Leakey and the East African Evidence* ed. by G. L. Isaac and E. R. McCown, pp. 97–116. W. A. Benjamin, Menlo Park, CA.

Broughton, J. M., D. Mullens, and T. Ekker (2007) Avian resource depression or intertaxonomic variation in bone density? A test with San Francisco Bay avifaunas. *Journal of Archaeological Science* 34(3):374–391.

Buckland, W. (1823) *Reliquiae Diluvianae, or, Observations on the Organic Remains Contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, Attesting to the Action of an Universal Deluge*. J. Murray, London.

Butler, V. L. and J. C. Chatters (1994) The role of bone density in structuring prehistoric salmon bone assemblages. *Journal of Archaeological Science* 21(3):413–424.

Cameron, J. R., J. G. Skofronick, and R. M. Grant (1999) *Physics of the Body* (2nd ed.). Medical Physics Publishing, Madison, WI.

Cann, C. E. (1988) Quantitative CT for determination of bone mineral density: A review. *Radiology* 166(2):509–522.

Carlson, K. J., and T. R. Pickering (2004) Shape-adjusted bone mineral density measurements in baboons: Other factors explain primate skeletal element representation at Swartkrans. *Journal of Archaeological Science* 31(5):577–583.

Chambers, A. L. (1992) *Seal Bone Mineral Density: Its Effect on Specimen Survival in Archaeological Sites*. B.A. Honors Thesis, Department of Anthropology, University of Missouri, Columbia, MO.

Cruz, I., and D. Elkin (2003) Structural bone density of the lesser rhea (*Pterocnemia pennata*) (Aves: Rheidae): Taphonomic and archaeological implications. *Journal of Archaeological Science* 30(1):37–44.

Currey, J. (1984) *The Mechanical Adaptations of Bones*. Princeton University Press, Lawrenceville, NJ.

Darwent, C., and R. L. Lyman (2002) Detecting the postburial fragmentation of carpals, tarsals, and phalanges. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 355–377. CRC Press, Boca Raton, FL.

Dawkins, W. B. (1869) On the distribution of British postglacial mammals. *Quarterly Journal of the Geological Society of London* 25:192–217.

Dawkins, W. B. (1874) *Cave Hunting, Researches on the Evidence of Caves Respecting the Early Inhabitants of Europe*. Macmillan, London.

Dirrigl, F. J. (2001) Bone mineral density of wild turkey (*Meleagris gallopavo*) skeletal elements and its effect on differential survivorship. *Journal of Archaeological Science* 28(8):817–832.

Elkin, D. C. (1995) Volume density of South American camelid skeletal parts. *International Journal of Osteoarchaeology* 5(1):29–37.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Fernández-Jalvo, Y., and P. Andrews (2016) *Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification*. Springer, Dordrecht.

Fernández-Jalvo, Y., P. Andrews, P. Sevilla, and V. Requejo (2014) Digestion versus abrasion features in rodent bones. *Lethaia* 47(3):323–336.

Frostick, L., and I. Reid (1983) Taphonomic significance of sub-aerial transport of vertebrate fossils on steep semi-arid slopes. *Lethaia* 16(2):157–164.

Galloway, A., P. Willey, and L. Snyder (1997) Human bone mineral densities and survival of bone elements: A contemporary sample. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 295–317. CRC Press, Boca Raton, FL.

Golda, S. DuP. (2015) *Intrinsic Properties of Bone as Predictors of Differential Survivorship*. Ph.D. Dissertation, University of Missouri, Columbia, MO.

Grayson, D. K. (1984) *Quantitative Zooarchaeology: Topics in the Analysis of Archaeological Faunas*. Academic Press, Orlando, FL.

Guthrie, R. D. (1967) Differential preservation and recovery of Pleistocene large mammal remains in Alaska. *Journal of Paleontology* 41(1):243–246.

Gutiérrez, M., C. Kaufmann, M. González, A. Massigoge, and M. C. Álvarez (2010) Intrataxonomic variability in metapodial and femur bone density related to age in guanaco (*Lama guanicoe*): Zooarchaeological and taphonomical implications. *Journal of Archaeological Science* 37(12):3226–3238.

Hill, A. P. (1980) Early postmortem damage to the remains of some contemporary East African mammals. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 131–155. University of Chicago Press, Chicago.

Hindelang, M., and A. L. Maclean (1997) Bone density determination of moose skeletal remains from Isle Royale National Park using digital image enhancement and quantitative computed tomography (QCT). *International Journal of Osteoarchaeology* 7(3):193–201.

Holt, S., D. Codron, and L. Kolska Horwitz (2018) Bone mineral density in the leopard tortoise: Implications for inter-taxon variation and bone survivorship in an archaeozoological assemblage. *Quaternary International* 495:64–78.

Holt, S., L. Kolska Horwitz, J. Hoffman, and D. Codron (2019) Structural density of the leopard tortoise (*Stigmochelys pardalis*) shell and its implications for taphonomic research. *Journal of Archaeological Science: Reports* 26:101819. DOI: 10.1016/jasrep.2019.04.008.

Ioannidou, E. (2003) Taphonomy of animal bones: Species, sex, age, and breed variability of sheep, cattle, and pig bone density. *Journal of Archaeological Science* 30(3):355–365.

Izeta, A. D. (2005) South American camelid bone structural density: What are we measuring? Comments on data sets, values, their interpretation and application. *Journal of Archaeological Science* 32(8):1159–1168.

Klein, R. G. (1989) Why does skeletal part representation differ between smaller and larger bovids at Klasies River Mouth and other archeological sites? *Journal of Archaeological Science* 16(4):363–381.

Korth, W. W. (1979) Taphonomy of microvertebrate fossil assemblages. *Annals of the Carnegie Museum* 48:235–285.

Kreutzer, L. A. (1992) Bison and deer bone mineral densities: Comparisons and implications for the interpretation of archaeological faunas. *Journal of Archaeological Science* 19(3):271–294.

Krumbein, W. C. (1941) Measurement and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Research* 11(2):64–72.

Lam, Y. M., X. Chen, C. W. Marean, and C. J. Frey (1998) Bone density and long bone representation in archaeological faunas: Comparing results from CT and photon densitometry. *Journal of Archaeological Science* 25(6):559–570.

Lam, Y. M., X. Chen, and O. M. Pearson (1999) Intertaxonomic variability in patterns of bone density and the differential representation of bovid, cervid, and equid elements in the archaeological record. *American Antiquity* 64(2):343–362.

Lam, Y. M., and O. M. Pearson (2005) Bone density studies and the interpretation of the faunal record. *Evolutionary Anthropology* 14(3):99–108.

Lam, Y. M., O. M. Pearson, C. W. Marean, and X. Chen (2003) Bone density studies in zooarchaeology. *Journal of Archaeological Science* 30(12):1701–1708.

Lubbock, J. (1913) *Prehistoric Times as Illustrated by Ancient Remains and the Manners and Customs of Modern Savages* (7th ed.). Henry Holt and Company, New York.

Lyman, R. L. (1984) Bone density and differential survivorship of fossil classes. *Journal of Anthropological Archaeology* 3(4):259–299.

Lyman, R. L. (1993) Density-mediated attrition of bone assemblages: New insights. In *From Bones to Behavior* ed. J. Hudson, pp. 324–341. Center for Archaeological Investigations Occasional Paper No. 21, Southern Illinois University Press, Carbondale, IL.

Lyman, R. L. (1994a) Quantitative units and terminology in zooarchaeology. *American Antiquity* 59(1):36–71.

Lyman, R. L. (1994b) Relative abundances of skeletal specimens and taphonomic analysis of vertebrate remains. *Palaios* 9(3):288–298.

Lyman, R. L. (1994c) *Vertebrate Taphonomy.* Cambridge University Press, Cambridge.

Lyman, R. L. (2008) *Quantitative Paleozoology.* Cambridge University Press, Cambridge.

Lyman, R. L., L. E. Houghton, and A. L. Chambers (1992) The effect of structural density on marmot skeletal part representation in archaeological sites. *Journal of Archaeological Science* 19(5):557–573.

Morlot, [K. von] A. (1861) General views on archaeology. *Smithsonian Institution Annual Report for 1860*, pp. 284–343.

Nicholson, R. A. (1992) An assessment of the value of bone density measurements to archaeoichthyological studies. *International Journal of Osteoarchaeology* 2(2):139–154.

Novecosky, B. J. and P. R. W. Popkin (2005) Canidae volume bone mineral density values: An application to sites in Western Canada. *Journal of Archaeological Science* 32(11):1677–1690.

Pavao, B. and P. W. Stahl (1999) Structural density assays of leporid skeletal elements with implications for taphonomic, actualistic and archaeological research. *Journal of Archaeological Science* 26(1):53–66.

Pickering, T. R. and K. J. Carlson (2002) Baboon bone mineral densities: Implications for the taphonomy of primate skeletons in South African cave sites. *Journal of Archaeological Science* 29(8):883–896.

Shipman, P. (1981) *Life History of a Fossil: An Introduction to Taphonomy and Paleoecology.* Harvard University Press, Cambridge, MA.

Smith, C. I., M. Faraldos, and Y. Fernández-Jalvo (2008) The precision of porosity measurements: Effects of sample pre-treatment on porosity measurements of modern and archaeological bone. *Palaeogeography, Palaeoclimatology, Palaeoecology* 266:175–182.

Smith, R. E. (2008) *Structural Bone Density of Pacific Cod* (Gadus macrocephalus) *and Halibut* (Hippoglossus stenolepis)*: Taphonomic and Archaeological Implications*. M.A. Thesis, Portland State University, Portland, OR.

Stahl, P. W. (1999) Structural density of domesticated South American camelid skeletal elements and the archaeological investigation of prehistoric Andean ch'arki. *Journal of Archaeological Science* 26(11):1347–1368.

Suby, J. A. and R. A. Guichón (2004) Densidad ósea y frecuencias de hallazagos en restos humanos en el norte de Tierra del Fuego: Análisis exploratorio. *Intersecciones en Antropología* 5:95–104.

Symmons, R. (2004) Digital photodensitometry: A reliable and accessible method for measuring bone density. *Journal of Archaeological Science* 31(6):711–719.

Symmons, R. (2005) New density data for unfused and fused sheep bones, and a preliminary discussion on the modeling of taphonomic bias in archaeofaunal age profiles. *Journal of Archaeological Science* 32(11):1691–1698.

Symmons, R. (2002) *A Re-Examination of Sheep Bone Density and Its Role in Assessing Taphonomic Histories of Zooarchaeological Assemblages.* Ph.D. Dissertation, University College London, London.

Turner, C. G., II, and J. A. Turner (1999) *Man Corn: Cannibalism and Violence in the Prehistoric American Southwest.* University of Utah Press, Salt Lake City, UT.

Voorhies, M. R. (1969) *Taphonomy and Population Dynamics of an Early Pliocene Vertebrate Fauna, Knox County, Nebraska.* University of Wyoming Contributions to Geology, Special Paper No. 1. Laramie, WY.

White, T. D. (1992) *Prehistoric Cannibalism at Mancos 5MTUMR-2346.* Princeton University Press, Princeton, NJ.

Whyte, T. R., and J. M. Compton (2020) Explaining toad bones in southern Appalachian archaeological deposits. *American Antiquity* 85(2):305–330.

Willey, P., A. Galloway, and L. Snyder (1997) Bone mineral density and survival of elements and element portions in the bones of the Crow Creek Massacre victims. *American Journal of Physical Anthropology* 104(4):513–528.

Zingg, T. (1935) Beitrage zur schatteranalyse. *Schweizerische Mineralogische und Petrographische Mitteilungen* 15:39–140.

Effects of Burial Environment on Osseous Remains

5

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Contents

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> Not a flower, not a flower sweet
> On my black coffin let there be strown;
> Not a friend, not a friend greet
> My poor corpse, where my bones shall be thrown:
> A thousand thousand sighs to save,
> Lay me, O, where
> Sad true lover never find my grave,
> To weep there!
>
> **—William Shakespeare**
> *Twelfth Night,* Act II, Scene 4

Introduction

One of the most basic questions that a forensic anthropologist working in a medical examiner's office or a similar setting must answer is whether remains are human or nonhuman. Once remains are identified as human, placing them into broad categories of postmortem history depends on the analytical approach, which largely derives from the taphonomic markers of their burial or other depositional setting (surface, water, etc.) (Berryman et al. 1991, 1997; Duhig 2003; Hughes et al. 2012; Micozzi 1991; Pokines 2018a, 2020; Schultz 2012; Schultz et al. 2003; Sledzik and Micozzi 1997; Ubelaker 1995). The taphonomic alterations left by different burial contexts (or lack thereof) and the duration of burial often separate remains into groups along the following lines: (1) recent remains, sometimes with associated soft tissue, that are of definite forensic interest; (2) cemetery remains, whether recent or not, that likely do not represent criminal activity other than the possibility of vandalism of buried remains; (3) remains derived from historical/archaeological burials, which normally become the responsibility of state archaeological agencies (Garman 1996); (4) remains likely derived from anatomical teaching, trophy, and/or ritual contexts, which probably have not been buried; and (5) unknown remains that do not fit easily into any of these categories (see Chapter 1, this volume). The analysis of taphonomic effects brought about by burial environments or the lack thereof is crucial in the categorization of human skeletal remains as being of forensic interest and their ultimate disposition.

General Effects of Burial Directly in Soil

Effects of Soil pH

General Soil Properties

The science of pedology is primarily the domain of agricultural and engineering concerns, but it also is a component of geological, geomorphological, archaeological, and forensic concerns. The forensic analysis of soils has numerous practical applications (Fitzpatrick 2008), and the characteristics of individual soils and components of soils examined include color, consistency, texture, structure, and inclusions. *Soils* form naturally through the complex interactions of *parent material* (the main source of mineral and/or organic materials in a given location, which may derive from sources including local bedrock, alluvial deposits, aeolian deposits, volcanic ash, or glacial deposits), topography (slope and drainage), climate (including temperature and precipitation), and biological organisms (including plants, fungi, and other decomposers, and *fossorial* or burrowing animals) over time. Soils are found on land surfaces and have distinct *horizons*, or types of layers (see below), that have changed from the parent material from which they formed (Soil Survey Staff 2014). Deep soils have taken centuries or millennia to reach their present forms but do not remain static. Soils also have complex interactions of air and groundwater within their porous structure. Disruptions in this structure are usually highly visible and are the primary clue to forensic archaeologists that a body has been buried recently in that location.

Soils have up to five common horizons, which should not be confused with the stratigraphy caused by human deposition. These main horizons usually are broken down into multiple subhorizons, although not all of these horizons are present for every soil, and some soils also have other types of main horizons (Soil Survey Staff 2014). The uppermost is the *O horizon*, which consists primarily of decomposing accumulated plant matter. Surface-deposited remains are often obscured by this horizon, as continued leaf fall will cover bones slowly and continue to decompose, gradually creating soil around and on them. The *A horizon* is normally equated with the topsoil, the organic-rich horizon that often is only centimeters deep yet contains most of the nutrients taken up by plants; it is also the site of the majority of the biotic activity. A commonly encountered subhorizon is that upper portion of an A horizon that has undergone plowing disturbance and is normally referred to as the Ap subhorizon (or the *plow zone*). The plow zone is of practical importance in both archaeology and forensics, as the process of plowing often brings buried objects to the surface, causing underground and above-ground dispersal (Haglund et al. 2002) as well as damage to the objects. The *B horizon* is characterized by the accumulation of soluble base minerals dissolved from the A horizon and is usually lighter in color due to its lesser amounts of organically derived carbon. The *C horizon* consists of the less-altered *parent material* that formed locally from the physical and chemical breakdown of the bedrock or was deposited from other sources. The *R horizon* consists of the broken-up local bedrock (or *regolith*). Bedrock itself is not a part of the soil, although it has a major effect upon the types of soils that form from it. Classification of types of soils varies by country, with one comprehensive system developed by the US Department of Agriculture currently recognizing 12 soil orders (11 mineral soil orders and one organic soil order), which are broken down, much like biological taxonomy, into local soils on a par with individual species (Soil Survey Staff 2014). Common soil orders include Mollisols (deep soils found in plains/steppe environments), Histosols (organic soils, including those forming in peat bogs and other wetlands), Oxisols (the heavily oxidized, red soils often encountered in the tropics and subtropics), and Spodosols (often found in areas of pine forest).

Generally, soils are their most acidic in the A horizon. This is primarily due to three factors: (1) the leaching of base ions (calcium, magnesium, potassium, etc.) out of this horizon, where they are often accumulated in the B horizon or remain dissolved and are transported away with the creeping groundwater; (2) the concentration of decomposing organic matter and the release of organic acids (including humic and tannin); and (3) carbon dioxide (CO_2) (produced by decomposing organic matter) dissolving into water to form carbonic acid. This difference in pH is more notable where the bedrock is high in base ions, especially limestone and its principal component, calcium carbonate ($CaCO_3$). Soils forming on limestone may be acidic in their upper horizons and basic or close to neutral in their lower horizons. Soils also tend to become more acidic over time, as more soluble base ions are lost and more organic matter accumulates.

Burial Depth

Given the chemical differences in soil horizons, depth of burial may play a significant role in skeletal preservation of buried remains. While folklore suggests that formal burials (i.e., those in cemeteries) are "six feet under", this legend does not hold true in practice. Historical cemetery burials have been found at depths as shallow as 2–4 feet below the surface (Dockall et al. 1996b:154; Fox 1984:28–29) and as deep as 5.5 feet (Taylor et al. 1986:15, 20). In the USA, modern state and cemetery regulations differ, with actual required burial depths ranging from 1.5 to 12 feet. For example, California's Health and Safety Code, §8113.1, requires that burials are covered by 1.5 feet of soil, while Article 205 of the New York City Public Health Law, §205.25, states that "…the top of the coffin or casket shall be at least three feet below the level of the ground, but if the coffin or casket is enclosed in a concrete or metal vault, the top of the vault shall be at least two feet below the level of the ground". Generally speaking, burial depth is governed by the height of the water table (e.g., most burials are above ground in cemeteries in New Orleans, Louisiana, USA; Yalom 2008:140), depth of topsoil relative to bedrock, and other intrinsic geological factors. In clandestine, temporary, or other expedient burials, gravediggers are likely to excavate only to the depth necessary to ensure that remains are not (or minimally) disturbed by scavenging animals. In most cases, whether the interments are in cemeteries or clandestine, burial shaft dimensions are only slightly larger than necessary to accommodate the coffin or body, respectively, and infant or child burials typically will be smaller and shallower than adult burials (e.g., Fox 1984; Gadus et al. 2002; Taylor et al. 1986).

High water tables, such as those seen at the Texas State Cemetery (Austin, TX) and the Phillips Memorial Cemetery (Galveston, TX), can result in poor preservation through softening of the bone not only due to chemical erosion but also as the result of mechanical erosion due to contact with coffin walls, other skeletal elements, or artifact inclusions in the casket (Dockall et al. 1996a,b). Skeletal elements may be removed from their anatomical position through oscillation of the water table. In one burial at the Phillips Memorial Cemetery, foot elements were found floating in water contained between the outer box and the coffin; in another, a humerus had been pushed against the end of the coffin (Dockall et al. 1996a; see also Dockall et al. 1996b:211). Effects like these may be particularly evident in the small bones of the hands and feet and among the lightweight thoracic elements.

Acidic Soil Corrosion

Perhaps the most pervasive long-term destructive force acting upon bones is soil acidity (Casallas and Moore 2012; Crow 2008). In depositional environments with near-neutral or slightly basic pH, bone preservation typically is excellent. This is particularly true for deposits in limestone caverns. Due to their sediment pH typically being in the 7.5–8.0 range, the protection that they afford from other destructive taphonomic forces (including subaerial weathering and sometimes scavenging), and a long time depth allowing for repeated occupation and deep accumulation, limestone caverns have yielded the bulk of hominin fossil history into the beginning of the Holocene. Other factors interacting with the effects of soil acidity include the amount of groundwater flow. In an acidic soil water solution, the hydroxyapatite crystals, $Ca_5(PO_4)_3(OH)$, are depleted of calcium (Ca^{2+}) ions by their replacement with hydrogen (H^+) ions (derived from hydronium ions, H_3O^+) as equilibrium is reached with the soil water (White and Hannus 1983). If the water flow rate is high in this acidic environment, the effect upon skeletal remains is the constant replenishment of hydronium ions in their immediate soil solution vicinity. Any acid neutralization effect brought about by the bones' mineral content itself is quickly negated. Similarly, the concentration of phosphate (PO_4^{3-}) ions in the soil-water solution reaches equilibrium with the hydroxyapatite, but these ions combine with iron (Fe) and aluminum (Al) in highly acidic solutions and precipitate out. Any increase in water flow rate may increase the dissolution of the mineral component of the bone (constituting about 70%), even in mildly acidic conditions. Crow (2008) found experimentally that mineral apatite was highly susceptible to dissolution with decreasing pH.

The gross morphological result of these (and other related) processes is *acidic soil corrosion*, which tends to appear on all exposed surfaces of a buried element, including interior spaces where these have become in direct contact with sediments/soil solution. The decomposition of the collagen component also contributes to the general pattern of bone deterioration, and the breakdown of the collagen can form acidic compounds that further the dissolution of the mineral component (White and Hannus 1983). The surfaces left behind may lose their smooth original texture and defined features, creating a scooped, irregular surface (Nicholson 1996). The loss is most apparent on epiphyses of long bones, where the cortical bone is thinnest and may be destroyed entirely through this process. Less dense bones such as the vertebrae, sternum, and innominates with thin cortices particularly prone to this taphonomic process. Casallas and Moore (2012) found that near-complete mineral dissolution occurred among a large sample of recent burials exhumed in Columbia after 8–10 years in a soil with a pH ranging from 4.2 to 4.5. In environments with extreme soil pH, high annual temperature, and high humidity, this type of osseous breakdown therefore can occur very rapidly. In cases of high acidity from artificial chemical sources, destruction of bone can be both high and very localized (Pokines and Springer 2016; Ubelaker and Sperber 1988).

Acidic soil corrosion gradually thins bone cortex such that small holes or *windowing* (Figure 5.1) may form in the weakened structure or expand from foramina. While the windowing and thinning caused by acidic soil corrosion are similar to that caused by gastric corrosion (Chapter 9), elements that are far too large to have been swallowed by any extant terrestrial scavenger may exhibit signs of acidic soil corrosion over their entire cortical surfaces. Bone that has been partially digested (deriving from vomit, digestive contents, or feces) consists of small whole elements (carpals, small phalanges, etc.) or highly fragmented larger bone (Pokines and Kerbis Peterhans 2007). Note also that a weakened structure is left behind on bone margins affected by acidic soil corrosion, while carnivore gnawing preferentially removes weakened areas, especially at the exposed ends of long bone diaphyses.

Bone preservation over the short term and long term is based upon a complex array of factors, including intrinsic bone properties, the actions of microbes, temperature, soil mineral composition, moisture, and soil pH (Child 1995; Hedges et al. 1995; Henderson 1987; Matthiesen et al. 2021; Mayne 2013; Nielsen-Marsh and Hedges 2000; Chapter 1). Soil pH also tends to alter over the short term of decomposition due to the influx of organic and mineral nutrients in a concentrated location, before returning to original or near-original levels (Benninger et al. 2008). The long-term pH to which bone is exposed, however, is largely dictated by the prevailing soil and climate conditions prior to deposition of a body.

The effects of acidic soil have been studied primarily in archaeological contexts due to the necessity for a significant burial duration to cause measurable differential preservation. For example, Gordon and Buikstra (1981) presented data from multiple Late Woodland Period burial mounds in Illinois, radiocarbon dating from AD 850 to 1200. These mounds

Figure 5.1 Acidic soil corrosion to distal human tibia. Note that while the windowing and thinning are similar to gastric corrosion, the element is far too large to have been swallowed and exhibits signs of corrosion over its entire cortical surface. Note also that a weakened structure is left behind, while carnivore gnawing preferentially removes weakened areas. The scale is in cm.

were constructed of silty loams overlooking major rivers. The remains included in the study came from 63 adult and 32 juvenile (<15 years old) skeletons and were categorized by the degree of preservation into five groups: (1) strong, complete bone; (2) fragile bone; (3) fragmented bone; (4) extremely fragmented bone; and (5) bone meal/ghost. These categories were compared with the pH from the burial fill, and a highly significant ($r = -92$, $p < 0.00001$, $n = 63$) inverse relationship (as pH decreases, destruction increases) was found for the adult remains. The relationship was not as significant with the juvenile remains ($r = -48$, $p < 0.005$, $n = 32$), likely due to the great changes in robusticity among remains of individuals over the first 15 years of life and the effect this has upon preservation independent of pH.

Overall, skeletal remains fared poorly when buried in more acidic soils, to the point of near disappearance in some cases. McCraw (2014) also found a negative correlation between overall skeletal preservation and duration of burial for a sample of sites from the West Central Illinois Valley, spanning the Late Archaic to Late Woodland periods, ~2500 BC to AD 1000. The indicators used to tally preservation included the total number of standard anatomical measurements that could be taken and the scorability of the pubic symphysis. While sex was not noted to be a factor in preservation, biological age was. Soil pH was not found to be variable enough among the locations sampled to show differential preservation. The experimental results of Christensen and Myers (2011) using sections of cattle (*Bos taurus*) long bone confirm that bones in extreme pH solutions (very low or very high) fare extremely poorly, while those closer to neutral pH were well-preserved after one year of submergence.

Nicholson (1996) found that while soil pH played a large role in bone condition over the course of a seven-year experiment, it was not the only determinant of bone preservation. She noted that surface etching was common among bones buried in acidic soils (in the pH 3.5–4.5 range). Nicholson (1998) further noted that bones buried for seven years in a compost heap were well-preserved upon excavation, but the pH in this particular depositional setting was neutral to slightly basic (7.0–7.5). A high organic content does not guarantee acidic soil conditions, and in this case, pH could have been elevated by the common inclusion of eggshells. Similarly, Mayne (2013) found only a moderate relationship between pH and skeletal preservation and stated that pH alone should not be used to create a predictive model for the preservation of skeletal remains. She also noted that the metal content of soils may influence pH levels and that soils of identical pH levels may have stark differences in levels of bone preservation, in part due to the collective effects of elements such as calcium (Ca) and aluminum (Al).

Effects of Soft Tissue Decomposition upon Soil pH

The decomposition of a buried body initially causes a large influx of organic acids, temporarily increasing acidity in its immediate vicinity. This stage is followed by the influx of base ions and therefore a general decrease in the acidity of the burial fill during the next phase of decomposition (Gill-King 1997; Wilson et al. 2007). As decomposition proceeds, the mildly alkaline local environment gradually returns to more acidic conditions as nutrient cycling and dissolution reduce the number of base ions in the burial fill. The overall effect of the burial of a whole or partial body in acidic soil is to postpone the onset of acidic soil corrosion, although the exact timing of these events is still being researched (Damann 2010).

Boot/Glove Taphonomy

Some buried objects may offer partial protection to bones. Improvised burials (such as those resulting from individual homicide, genocide, or warfare; Chapter 10) or modern embalmed burials commonly include leather footwear (Berryman et al. 1991, 1997; Iserson 1994; Rogers 2005). In contrast, early historical burials often do not include shoes or boots, either because they were passed down to family members due to their value or because shoes are difficult to put onto a dead body and would not be seen by mourners during a viewing anyway (Bond et al. 2002:154; Fox 1984:12, 14, 40; also see Rose 1985: Appendix, who found evidence of shoes in 10.1% of burials at Cedar Grove Cemetery in Texas). Leather is often preserved in acidic soils, as the acidity may provide an antiseptic effect to bacterial decomposition of the leather, and tanning hides acts to preserve them. Janaway (2008) noted the resistance of leather to decay when compared with other articles of clothing, including frequent finds in WWI field burials in Europe where all fabric had decomposed, but leather boots were still recognizable nearly 100 years later. The persistence of leather footwear (and potentially leather gloves) may provide a temporary, partial barrier to other destructive taphonomic effects of burial, including reduced direct contact with acidic soil, restricted acidic groundwater flow, lessened access by plant roots, and decreased potential for disturbance by fossorial taxa. This pattern of preservation may be made more apparent by the survival of the leather items until the time of excavation, but preferential survival of these relatively delicate hand and foot elements may indicate the former presence of leather items. The protective effect of leather boots often includes not only the foot elements but the distal portions of the tibia and fibula as well, which may be very well preserved, while the midshaft and proximal portions are in far more degraded condition (Pokines 2009). These types of leather items also offer some protection against other non-soil-related taphonomic processes, including plowing and other types of mechanical subsurface disturbance, such as trenching (Haglund et al. 2002; see "Effects of Plowing on Buried Remains" section, below). Similar effects have also been noted with buried cranial remains contained within military helmets (pers. obs.).

Special Case of Boreal Forests

Soils associated with coniferous forests (pines, etc.) often have a highly acidic topsoil with a much more benign subsoil. These frequently are classified as Spodosols, following the USDA system (Soil Survey Staff 2014), and are found in large areas of North America and Eurasia. Skeletons from shallow burials in these contexts often become exposed to highly acidic soil only in their uppermost portions—typically the anterior skull and innominates for bodies in a supine position. Over years of exposure, this can lead to highly localized acidic erosion of these portions of the skeleton, while the remaining portions are in a much better state of preservation. This process can lead to a "melted face" pattern of skeletal recovery (pers. obs.). Of course, any portion of the skeleton deposited near the upper portion of the burial may be affected in this manner, including hand and foot elements deposited on the upward-sloping edges of the burial feature. Since the mixed burial fill deriving from both the topsoil (highly acidic) and subsoil (less acidic) will start out with an average pH between these two extremes, the increased acidity of the upper portion of the burial fill must accrue over time through normal soil formation processes. This taphonomic pattern therefore is likely to appear only on skeletons that have been buried for multiple decades, including WWI and WWII field burials in the European Theater (pers. obs.).

Plant Root Invasion

Bones are a potential source of highly concentrated nutrients to plants, especially their nitrogen (N) and phosphate (PO_4^{3-}) content. Indeed, ground-up bone (bone meal) is a commercial organic fertilizer, applied primarily for its slow release of phosphate properties. It also reduces soil acidity through the addition of base ions, including calcium (Ca^{2+}). In the case of buried bones, the fine lattice structure of trabecular bone greatly increases the surface area for potential release of these nutrients into the environment, and this surface area initially increases as the bone gets more degraded and pores are expanded through dissolution of the mineral content and breakdown of the organic content. In addition, the porous structure of bone can trap water, further promoting the growth of plant roots through them and increasing the amount of direct contact between the two. Plant roots reaching a buried bone may grow preferentially around and into this microenvironment (Figure 5.2). Plant roots also may grow incidentally through foramina, including through the sacrum, vertebrae, cranium, and pelvis. Subsequent increase in the diameter of the root may destroy bone from the inside (Figure 5.3).

Gabet et al. (2003) summarized the bioturbation effects of plant roots and noted that the potential force of growing roots is enormous and can fracture apart planes in bedrock. Radial pressures have been noted to reach up to 0.91 MPa (910,000 N/m^2 or 132 lb/in^2). Root hairs can penetrate fissures as narrow as 100 μm, and tree roots have been found 6–7 m deep within otherwise solid granite. The ability of bone to withstand this force is therefore limited, especially under tension from penetrating roots expanding in diameter. Plant

Figure 5.2 Plant root invasion of a human tibia, forensic burial, Massachusetts, USA. The scale is in cm.

growth around a buried skeleton also may have been promoted previously in that location through the influx of nutrients from the decomposing soft tissue, further increasing the amount of root invasion into the bones. This potentially destructive process, however, also may contribute a form of postmortem interval (PMI) determination to the analysis of buried skeletal remains in the form of a minimum time since burial, since tree roots also develop annual rings that can be counted (Pokines 2018b; Willey and Heilman 1987), and even smaller plant root structures may aid in determining shorter (<1 year) PMI intervals (Quatrehomme et al. 1997).

Figure 5.3 Secondary urn burial, undisturbed, Icla Valley, Bolivia, Tiwanaku period. Note the plant roots growing through the tibia have nearly destroyed it from within, while the rest of the bones are in much better condition.

Plant roots also may destroy bone through the contact of the roots, leaving behind a pattern of surface damage in cortical bone known as *root etching*. Plant roots secrete multiple compounds (exudates) for a variety of purposes, which include aiding the uptake of minerals from the soil solution, deterring herbivory, acting as chemical attractants and repellents, increasing the abundance of helpful (symbiotic) bacteria, and inhibiting the growth of plant competitors (De-la-Peña et al. 2010; Walker et al. 2003). Some of these compounds include mild organic acids such as humic, citric, malic, and oxic, which may increase the available phosphorus for uptake by the plant (Bais et al. 2006; Rudrappa et al. 2008). These acidic compounds may dissolve the mineral content of the bone where the roots have grown in contact with it. Lyman (1994:376) also summarized the conclusions of multiple researchers who have noted that the microorganisms in association with the root (fungi, etc.) or the decomposition of the root itself may produce some of the acidic compounds likely responsible for the majority of bone damage. Individual root etchings likely are produced from a variety of processes related to the roots themselves.

Root etching patterns are typically meandering and branching (Figure 5.4), with a U-shaped profile to the individual surface scores (Lyman 1994:376). D'Errico and Villa (1997) and Morlan (1984) noted that root etching has been mistaken for incised markings on bone, including from deliberate butchery, artwork, or accidental mechanical abrasion, and that natural anatomical features including vascular grooves on the surfaces of bones have been mistaken for all of these. D'Errico and Villa (1997:11–14) noted that under high magnification, vascular channels can be seen to "tunnel" into the bone. Markings caused by sharp objects such as knives cutting into the surface of bone, regardless of the purpose or intent, should leave V-shaped profiles and parallel striations within the markings (Fisher 1995). These characteristics, which can be used to separate these types of surface marks from root etching, are summarized in Table 5.1.

Root etching also can form on the side of a bone in contact with the soil among surface-deposited remains (Figure 5.4), even while the more exposed side undergoes weathering

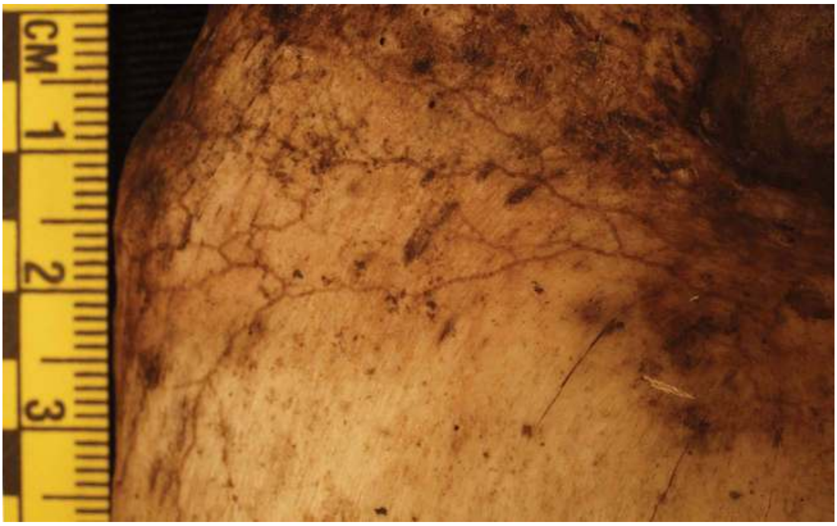

Figure 5.4 Root etching and staining (network of branching, fine dark lines) on clothed human innominate recovered from a surface scene, Massachusetts, USA, after two years of deposition. The scale is in cm (Pokines 2016:65; used with permission, *Journal of Forensic Identification*).

Table 5.1 Comparison of Surface Markings That May Be Mistaken for Root Etching in Forensic Contexts

Type of Surface Marking	Characteristics	Sources
Root etching	U-shaped groove profile; meandering/branching pattern; roots often still present; dark soil staining often present; follow surface contours of the bone.	D'Errico and Villa (1997); Fisher (1995); Morlan (1984); Lyman (1994)
Vascular grooves	U-shaped groove profile with rounded edges; branching pattern; some "tunnelling" into bone; funnel-shaped openings; follow surface contours of the bone.	D'Errico and Villa (1997)
Cut marks	V-shaped groove profile; linear pattern; striations within marks; often concentrated in multiple small areas on a bone; do not follow surface contours of the bone.	D'Errico and Villa (1997); Fisher (1995)
Abrasion marks	V-shaped groove profile; curving or meandering; multiple marks often created in parallel; many small, unpatterned marks.	D'Errico and Villa (1997); Fisher (1995)

(Chapter 11) and algae formation (Chapter 12). The root-etched lower side normally also has staining from the topsoil and may have some acidic soil corrosion (see "Acidic Soil Corrosion" section, above). Rootlets are often found sticking out of open structures in bones (Figure 5.5) and are an important indicator of previous (at least partial) burial or topsoil contact. Once a mat of roots has been removed from a bone surface, however, it may

Figure 5.5 Human cranial vault with plant roots growing through suture lines, forensic burial, Massachusetts, USA. The scale is in cm.

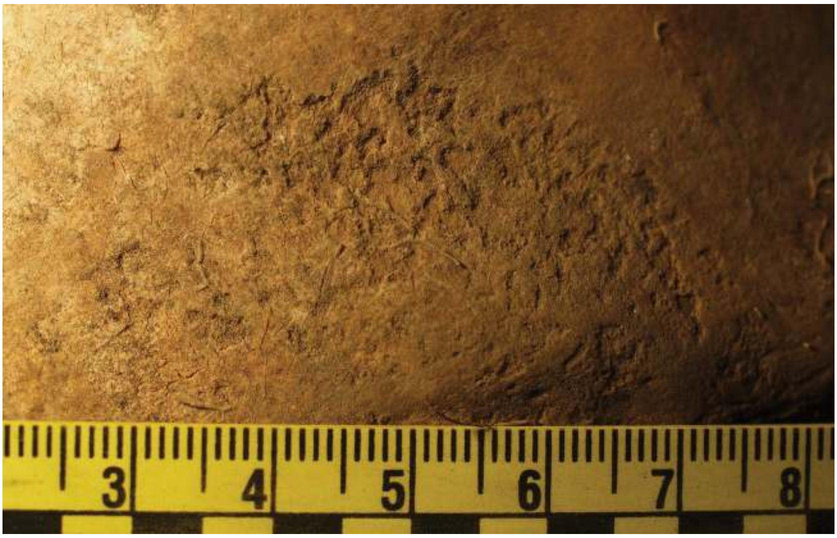

Figure 5.6 Human cranial surface after a portion of an adhering/invasive plant root mat has been removed, leaving behind an irregular eroded area. The scale is in cm.

leave an irregular eroded area of bone loss (Figure 5.6). This observation may indicate that the remains have been removed from a previous location when later recovered from a surface setting or if acquired from an unknown provenience. Rootlets also may leave darker staining of bones along their paths (see Figure 12.14, Chapter 12, this volume) in addition to etching or invading the surface.

Other Biological Attack

Other organisms besides plants utilize buried bone and associated soft tissue as a source of nutrients and thereby may leave behind surface damage on bone (Child 1995). Primary among these are members of the Kingdom Fungi, which along with bacteria are the major decomposers in most ecosystems. (The microscopic effects of these organisms upon bone are covered in Chapter 2.) Fungi also may leave behind macroscopic surface damage to bone, and this effect may occur in conjunction with the exudates of plant roots, as noted above. The major structures of fungi include hyphae, which are the thread-like structures that give many molds their fuzzy appearance. These can invade the porous structure of bone and leave behind focal damage (Jans et al. 2002). They also may grow on the surface of bone in large masses, often initially feeding on the soft tissue still attached or the residual organic content. The overall effect is to leave behind a roughened, eaten-away surface that forms through acidic dissolution, similar to acidic soil corrosion. Fungi are so ubiquitous in the upper horizons of the soil that large portions of the damage caused by the more general process of acidic soil corrosion may in fact be due to these species operating in conjunction with inorganic chemical reactions of dissolution of bone minerals. Fungal damage also may leave behind much more localized patches of surface erosion, with irregular edges (Armour-Chelu and Andrews 1996; Nicholson 1996, 1998). Andrews (1995) found areas of localized surface fungal attack (with some remaining fungal hyphae associated) on bones buried for 32 years as part of a long-term taphonomic experiment.

Termites also have the potential to consume buried bones, likely due to dietary nitrogen deficiencies. These processes are covered in Chapter 18, but the presence of termite alteration to bone suggests previous burial.

Bioturbation of Skeletal Remains

Species living within the soil may disperse bone (through the processes of *bioturbation*), which must be noted both for bone recovery and to prevent misinterpretation of this displacement as having to do with perimortem actions (Gabet et al. 2003). Armour-Chelu and Andrews (1994) examined the potential of earthworms (Oligochaeta) to displace buried microvertebrate bones and found up to 20 cm of vertical displacement within the soil column and up to 15 cm horizontal displacement over the course of three years. The results indicate that even earthworm bioturbation has the potential to move or at least shift the orientation of smaller human elements, such as hand and foot bones.

The impact of larger fossorial taxa, such as among the Rodentia (including gophers), Lagomorpha (including rabbits and hares), Mustelidae (weasel family), and Talpidae (mole family), upon site deposits is well known to archaeologists and geomorphologists (Bocek 1992; Gabet et al. 2003; Johnson 1989; Villa 1982). These taxa, with their large tunnel systems, potentially can displace even larger human bones. In some cases, this shifting can be marked, as in the case of a primary (and otherwise intact) individual burial from the Texas State Cemetery in which the left patella was discovered in the vicinity of the right hand (Dockall et al. 1996a). Bone displacement and loss from buried remains therefore cannot be assumed to have resulted from perimortem processes (trauma, etc.) where the potential exists for these taxa to have tunneled through a burial (Fox 1984:39). Indeed, the same types of easily tunneled soil that attract these animal species also may attract individuals undertaking clandestine burial activities, who typically rely on speed to avoid detection. Due to later infilling and tunnel collapse, the previous presence of burrows through a human burial may not be obvious during excavation. However, in some cases, the agent of disturbance may be made clear—down to a particular taxon—through the inclusion of faunal remains in the burial itself, such as a rodent skeleton recovered from casket fill (Dockall et al. 1996a:100).

Bioturbation should not be mistaken for the natural displacement of skeletal remains as the connective soft tissues decompose and disappear and as gravity takes on a more important role in their disposition upon excavation (Mickleburgh and Wescott 2018). Bodies in a direct soil burial necessarily undergo some kind of skeletal displacement as this process occurs and skeletal elements slowly gain additional space in which to move as the soft tissue decomposes. Sediment compaction from the burial fill pressing down also will shift the position of some elements, as may infilling sediments from water flow. Roksandic (2002) notes that skeletal displacement is a function of gravity and the architecture of the available empty space but is also influenced by the placement of the element(s) relative to the sequence of decomposition and subsequent disarticulation: a hand placed flat on the bottom of the grave will have its individual elements undergo little displacement, but a hand placed over the abdominal area will undergo much greater displacement and perhaps disarticulation of individual elements. These effects may be multiplied within mass graves, particularly where bodies overlay other bodies, where the bulk of soft tissue is much greater, and where the potential for movement, disarticulation, and commingling of individual elements increases (pers. obs.).

Soil Staining

Bones tend to take on the color of the medium into which they are deposited, due to their porous, wicking structure and initially pale coloration. Specific types of staining caused by different mineral deposits, including iron and copper oxides, are frequently encountered on buried remains (Janaway 2008) and are covered elsewhere in this volume (Chapter 12). Staining is, however, an important and ubiquitous taphonomic effect that may indicate the previous burial of a bone. For example, bone surfaces in contact with dark topsoil tend to become stained dark brown, with uniform staining more consistent with burial, and patchy or localized staining more consistent with surface deposition (see Figures 12.2 and 12.13, Chapter 12, this volume). It is likely that organic compounds, in particular the tannins, are primarily responsible for this color change (Barbehenn and Constabel 2011; Pollock 2017; Pollock et al. 2018). Carbon resulting from organic breakdown is a likely source of bone darkening. Bones buried in highly oxidized red clay soils, however, tend to take on reddish staining from this source of pigment. Nicholson (1996) noted areas of pink or mauve staining on osseous remains due to mold growth, which also has been noted by the authors in other contexts. This process is highly variable and requires additional research into the color changes possible from mold growth and the durability of these changes in a burial setting after the mold has died (Chapter 12).

Few data exist on the amount of time required for bone to take on environmental staining. Nicholson (1996) noted that in a taphonomic study of various whole, fleshed, or portions of various vertebrate species buried and recovered seven years later, very delicate recovery methods were needed, since the bones frequently had taken on the color of the surrounding sediments within that interval. These included tiny bones from rodents and fish. In order to standardize taphonomic color data gathering, Munsell® Soil Color Charts (Kollmorgen Instruments Corporation 1994) should be used to standardize observations (cf. Ruck and Brown 2015). Analysis of forensic cases with known intervals between the time of burial and recovery may reveal patterns regarding the rapidity of this process and its potential use in PMI estimation, even as a gross estimate, or to match remains with their depositional context.

Adipocere Formation

Buried remains may be associated with residual *adipocere* formation, or saponified fat tissue, which is sometimes referred to as grave wax (Chapters 3, 7, and 10). This substance normally ranges in color from white to gray to beige, and its consistency can range from soft and paste-like in its early stages to brittle and crumbly as it ages and dries (Schoenen and Schoenen 2013; Ubelaker and Zarenko 2011). Adipocere develops from any body fat tissue under moist, anaerobic conditions (Takatori 2001). Chemically, neutral fat triglycerides hydrolyze into fatty acids, which are then converted into insoluble hydroxy and saturated fatty acids from the actions of anaerobic bacteria, including *Clostridium perfringens* (O'Brien and Kuehner 2007). Temperature plays a role (O'Brien and Kuehner 2007), although cooler temperatures slow down (but do not seem to halt) the process (Kahana et al. 1999). Adipocere can occur in multiple types of depositional environment and may form in soil (Fiedler et al. 2009; Forbes et al. 2005), freshwater (O'Brien and Kuehner 2007), saltwater (Kahana et al. 1999; Chapter 7), and coffin (Ubelaker and Zarenko 2011) environments. Once formed, adipocere can persist for centuries or millennia. Fiedler et al. (2009)

found that adipocere persisted for 1600 years in the case of a Late Roman period infant buried in a stone sarcophagus near the Rhine River in Mainz, Germany. In that instance, the seasonal changes in groundwater level meant that the environment ranged from moist to inundated, and the adipocere had formed a hard, cement-like crust that aided the preservation of the skeletal remains. Adipocere formation also may account for the traces of apparent brain tissue contained in some crania from Windover Pond, Florida, USA, a large cemetery site in a wetland that dates back ca. 7000 BP (Stojanowski et al. 2002).

When dried, adipocere can form a light-colored, flaky scale on bones (see Figure 7.1, Chapter 7, and Figure 12.4, Chapter 12, this volume). Since it is not unique to terrestrial burial environments, it cannot be used as a taphonomic indicator of such. Its presence does imply deposition of the body in a protected environment (where soft tissues could not be consumed quickly by scavengers) with restricted access to oxygen (e.g., buried or inundated). In otherwise porous, sandy soil, adipocere still may form and persist for decades at the bottom center of mass burials and/or where remains were contained in a sealed plastic bag for over three decades (pers. obs.).

The dynamics of bodies in mass burials undergoing decomposition processes (Chapter 3) are too numerous to discuss here, although the history of investigations of these scenes is described in Chapter 10. In general, the processes of decomposition are slowed for the main mass of bodies, but while many taphonomic processes of bodies buried in soil continue more or less as usual (soil staining of bone, root etching and invasion, settling, etc.), others are enhanced (commingling). One important observation is the *feather edge effect* (Haglund 2002), where bodies deposited at the margins of mass burials tend to decompose and skeletonize more rapidly than the bodies in the central mass of remains, where the pooling of decomposition liquid can promote adipocere formation toward the bottom and center of the mass (pers. obs.). Bodies at the periphery also have a greater surface area in direct contact with soil minerals, organisms, oxygen, and groundwater flow compared with bodies packed together in the center of mass, which likely leads to the more rapid skeletonization of the former. Individuals recovered from the same mass grave may be in very different decomposition stages, including the degree of adipocere formation; lacking contextual data, an analyst might assume that they came from two different burials entirely.

Effects of Plowing on Buried Remains

Plowing of agricultural fields both benefits and imperils forensic anthropological practice. Shallow burials in fields are often impacted by plowing, and the dispersal of bone across the freshly plowed (and therefore plant-denuded) surface makes the central burial location potentially much easier to locate. This mechanized destructive force, of course, may damage the very remains that are being sought, dispersing them over a wide area and thereby increasing the time required for and difficulty of recovery, and may cause damage that could be mistaken for perimortem trauma. Plowing also mixes the topsoil, which may destroy evidence of the burial feature and the information that it may contain in terms of the tools used to excavate it, its postdepositional history, and other data such as footprints or other impressions (Hochrein 2002). Agricultural fields also may be an attractive place for clandestine burials, despite their lack of cover, as these events frequently take place at night (Chapter 10). The lack of tree root systems and expected deep soil allows for more rapid grave digging, and perpetrators may expect that later plowing will obscure any surface signs of digging. Plowing effects (damage and dispersal) on bone therefore are not uncommon.

The direct damage to skeletal remains caused by modern plowing has three main sources: the impact of the plowing, harrowing, seeding, or other multibladed heavy implement drawn through the soil; the abrasion caused by dragging through sediments; and the crushing caused by the wheels of the traction vehicle pulling the implement. The first type of postmortem damage can be reflected in fragmentation of the bone or by visible gouges into the bone caused by both blunt and relatively sharp metal surfaces (Haglund et al. 2002). Abrasion caused by movement through the soil is similar to that caused by trampling and other accidental impacts leaving surface striations (Table 5.1) (Andrews and Cook 1985; D'Errico and Villa 1997; Fisher 1995). Heavy machinery rolling over bone may cause massive crushing damage, which may get obscured by subsequent fragment dispersal.

Dispersal of remains is an equally important effect of plowing. While the increased recovery effort and loss of some remains are problem enough, the dredging up of bone from a burial context to the surface also changes its taphonomic environment. Bone buried in an agricultural field is exposed to the common taphonomic processes discussed in this chapter, including plant root invasion, soil staining, and acidic soil erosion. Subsequent surface exposure and its associated taphonomic processes, including subaerial weathering and scavenger gnawing, may overwrite those earlier taphonomic alterations and obscure the prior history of burial (Chapter 20). Plowed remains therefore likely combine a suite of taphonomic characteristics from both buried and surface regimes. Individual fragments or portions of remains buried at the same time but from this type of context may display markedly different preservation due to these disturbances. Remains that have surfaced as a result of plowing may show a high degree of cracking, exfoliation, and sun bleaching, while those that remained buried may be in a much better state of preservation. Context of recovery is an important consideration when determining depositional history and PMI using taphonomic indicators, and such disparate taphonomic states in a single set of remains should not result in an automatic assessment that the remains came from multiple depositional episodes.

Odell and Cowan (1987) used an experimental setting to determine the mechanical plowing movement potential of archaeological artifacts, in this case stone tools painted for easier detection. They found in their own research (consistent with previous research on the topic) that the average recovery rate of surface objects from their large initial (n = 1000) buried sample was 5.6% over all runs. This percentage may not reflect the surface recovery rate for bone, given that fragile bones may be highly fragmented by plowing impacts and dragging, so the number of individual bone pieces will likely increase over time for osseous items in plowed contexts. Surface detection rates for bone fragments might be decreased by their blending in with soil cover in the case of recently uncovered remains but also might increase in cases where prolonged surface exposure leads to their sun bleaching (Chapter 11), thus increasing their visibility to survey teams. Small bleached fragments by themselves may be nondiagnostic, but their presence on the surface may lead to finding larger diagnostic bones. Fragmented bone may have lighter internal surfaces relative to external surface staining, so these fragments also may stand out in contrast to dark topsoil. Odell and Cowan (1987) further noted a cumulative mean horizontal movement of their artifacts of over 2 m, with the site doubling in area as measured by the perimeter created by its farthest outliers after 12 plowing runs. A greater average displacement was noted along the primary axis of plowing. Haglund et al. (2002) noted in a case study from Cyprus where 23 years of plowing in a barley field had displaced most remains from a shallow burial, leaving only some right and left foot elements *in situ*. The dispersal of these remains may have been hindered by the temporary presence of leather footwear. Human skeletal remains were scattered a maximum of 32 m east-west and 14 m north-south. The local machinery plowed to a maximum depth of approximately 25 cm.

Newcomb (2015) and Newcomb et al. (2017) performed an experiment to examine more specifically the effects of plowing upon shallow graves, similar to what may occur in cases of clandestine burial. This research used already decomposed juvenile pig (*Sus scrofa*) skeletons buried in relative anatomical position at 15 cm and 22 cm below surface. Five burials were made at each depth, and the burials were then mechanically plowed one, three, five, seven, or 10 times in alternating directions. The plow type was mechanical disk, normally used in this location for annual weed control. The surface skeletal material was recovered using pedestrian survey and mapped with a total station, then the area was excavated by hand including screening 1-×-1-m units with a 1/4 inch (6.4 mm) mesh. A significant relationship was noted between the degree of plowing and overall recovery for the percentage of recovery of undamaged elements. The rate of recovery decreased from 88.9% for the shallower burial with one plowing pass down to 55.5% for the shallower burial that underwent ten plowing passes. The higher recovery rate for deeper burials indicated that greater depth protected the remains to a greater degree, an effect that was not significantly decreased with higher numbers of plowing passes. The distance that skeletal elements were displaced also increased with the number of plowing passes. After one pass at either depth, all recovered elements came from the initial 1-×-1-m unit containing the burial. After ten plowing passes, overall dispersal increased to 12 m for the shallow burials and 4 m for the deeper burials. The long axis of dispersal in the case of both depths was parallel to the direction of plowing, with some lateral dispersal also detected. More passes or more directions of passes, reflecting situations with multiple years of plowing, likely would have brought about more bone damage and dispersal.

Special Natural Burial Environments

Some natural burial environments, while rare in forensic settings, pose particular suites of taphonomic characteristics that should be recognizable due to the presence of large amounts of preserved soft tissue typically associated with the skeletal remains. The excellent soft tissue preservation therefore makes these types of burials potentially mistakable, at least initially, for more recent remains and may attract initial concern from the public or law enforcement when encountered. In addition, natural mummification may occur rapidly, so naturally mummified remains are often encountered in forensic contexts (Galloway et al. 1989).

Mummification

There are two types of mummification: artificial, most famously from ancient Egypt, and natural (Mayer 2012; Micozzi 1991). Artificial or deliberate mummification is done typically as part of an elaborate postmortem ritual in which the remains are displayed for some time after death. Natural mummification may occur in dry environments, such as after interment in sand or other very well-drained soils in arid climates and in dry, cold environments. For example, the mummies of Xianjiang, China, are the desiccated bodies of what appears to be a family of four, naturally mummified after being buried in the stony desert of northwest China (Hadingham 1994). Similarly, naturally mummified bodies have been found in environments as diverse as the Peruvian and Argentinean highlands and Mammoth Cave in Kentucky, USA, while cemeteries in Guanajuato, Mexico, are well known for their naturally mummified remains (Iserson 1994:216). Furthermore, modern forensic cases sometimes include naturally mummified remains in homes where the air is very dry or outdoors in desert environments (Galloway et al. 1989).

Ice Burials

The long-term preservative effects of frozen environments upon soft tissue are well known (Micozzi 1991, 1997) and require little elaboration here. The most famous recent example of this process is the 1991 find of the frozen remains later dubbed "Ötzi" at an altitude over 3200 m in the Italian Alps. These remains have been radiocarbon dated to ca. 3300 BC (Chalcolithic Age), with associated artifacts confirming this date (Ruff et al. 2006). Discovered melting out of a glacier, these largely intact (although desiccated) remains were found in such good condition that they were mistaken initially for a recent alpinist death. The excellent preservation included the internal organs and recognizable stomach contents (Gostner et al. 2011), soft tissue evidence of the cause of death (an arrow wound to the left shoulder), and an unrelated hand wound (Vanzetti et al. 2010). Preservation was similarly excellent for fragile artifacts associated with the body, including leather and woven grass clothing and equipment items. Long-term preservation in such settings is greatly enhanced by actual covering by snow/ice to exclude scavengers and greater tissue loss from decomposition during thawing spells and wind abrasion. The slowly degrading sets of exposed remains from recent alpinist deaths among those attempting Mount Everest, which have been exposed to sun and wind, are testament to the potential for long-term preservation in these types of environments. Clearly, in more benign conditions over shorter (typical forensic) PMIs, large amounts of soft tissue preservation are expected in these environments.

Other recent cases of note include the separate finds of two WWII aviators who crashed on a glacier in 1942 California, USA (Stekel 2010), and who were identified by the Joint Prisoner of War/Missing in Action Accounting Command's Central Identification Laboratory (CIL), Hawaii, USA. Pilloud et al. (2016) also reported the recovery of human remains by the CIL from the Colony Glacier, Alaska, USA, where a C-124 (four-propeller engine) military transport aircraft carrying 52 personnel crashed in 1952 at an altitude of 2400 m in the accumulation area of the glacier. No recovery was possible at the time, so the location was lost, and the remains got buried by snow that slowly turned into glacial ice. The crash was rediscovered in 2012, a full 18 km downslope due to glacial movement. Two recoveries of surface remains were required, in 2012 and 2013, due to additional remains melting out, with more remains still unrecovered in the glacier. Types of taphonomic observations on the bones included: (1) fractures consistent with rapid deceleration; (2) abrasion/damage of bone margins; (3) splitting of bone ends (giving a frayed appearance in some cases); (4) sun-bleaching; and (5) significant soft tissue preservation and adipocere formation. Taphonomic effects included dispersal of remains by the glacial movement, the pace of which averaged over 300 m per year.

Bog Burials

Bogs (wetlands characterized by the accumulation of decomposing plant remains, typically mosses of the genus *Sphagnum*) also have the potential to preserve soft tissue long term and thus cause archaeological or historical remains to be mistaken for remains of forensic interest (Brothwell et al. 1990). These remains may be encountered by accident or through commercial activities including peat harvesting. The bog burial environment is characterized by acidic water high in tannins, aerobic conditions, and large scavenger exclusion. These factors combine to allow excellent preservation of soft tissue (and organic artifacts), with skin tanning into a leather-like consistency, lesser preservation of internal organs, and demineralization of osseous elements (Brothwell et al. 1990; Micozzi 1991; Stødkilde-Jørgensen et al. 2008). Adipocere formation also is common in these environments (Evershed 1992). Deliberate burial (as opposed to simply falling into a bog and becoming buried naturally over time) apparently is a necessary ingredient for preservation, as so few animal bog bodies are known from the same European contexts that have yielded many human examples (Wilkinson et al. 2006). Ancient bog bodies also tend to be accompanied by a suite of other characteristics, including frequent lack of clothing, ligatures from strangulation, and other signs of perimortem trauma (Brothwell et al. 1990). Context, including accompanying artifacts, may remove remains of this origin from further forensic consideration.

Cemetery Remains

Cemetery remains are frequently encountered from disturbed recent contexts and are turned in to law enforcement for subsequent evaluation by forensic anthropologists. These cases can form a significant portion of the human remains received in a medical examiner setting (pers. obs.), perhaps being more common in regions with longer settlement histories and large amounts of older, less well-marked cemeteries. Construction projects, erosion, natural disasters such as hurricanes and floods, deliberate vandalism, or purposeful theft in order to obtain human remains for religious activities (Chapter 8) all may expose cemetery remains. Fortunately, the taphonomic characteristics typical of coffin burials are some of the best-researched in forensic anthropology (Berryman et al. 1991, 1997; Nawrocki 1995; Rogers 2005; Schultz 2012; Schultz et al. 2003; Sledzik and Micozzi 1997), likely due in part to the practical importance of and frequent need for distinguishing remains of this origin from the remains of recent homicide victims.

General Effects of the Coffin Environment

Coffins do not present a constant burial environment, as coffins also proceed through a process of gradual breakdown. Their temporary nature is especially true in the case of wooden coffins. The coffin environment initially provides physical protection for a set of remains, which may have been given additional protection from decomposition by embalming. This physical protection may include initial prevention of direct contact with burial sediments and their destructive biota, including plant roots, bacteria, fungi, and other organisms that would utilize the remains as a source of nutrients or disturb them through fossorial activity (see Haglund 1991; Rodriguez and Bass 1985). Buried remains may decompose more slowly than those exposed on the surface not just due to physical protection from necrophagous insects and microorganisms but also because the temperature underground may be lower (Rodriguez and Bass 1985). Coffins, of course, need not be buried at all but may be placed in an above-ground mausoleum, further hindering the biological attack upon skeletal remains. In the USA (including Massachusetts, where one of the authors [JTP] is based), a concrete burial vault often is required by the cemetery to protect the coffin itself and to prevent subsidence of the burial fill. Vaulting was also practiced in some locations historically, where additional wooden planks were placed over the top of the coffin for protection (sometimes referred to as a "dug vault"; Taylor et al. 1986:4). The main shaft was excavated wider than the coffin, and then a smaller hole was excavated at the base that fit the coffin more snugly. The resulting earthen shelves on either side supported planks that covered the coffin and afforded some immediate protection from the burial fill (Davidson 2012; Pye 2007; see also Fox 1984; Taylor et al. 1986). Locally obtained stone (e.g., sandstone) was used to create vaulted crypts in some nineteenth-century rural cemeteries, although commonly they covered in-ground burials (Fox 1984:15, 53).

Beginning in the late twentieth century, vaults have been manufactured from many materials, including copper, aluminum, and fiberglass (Mitford 1998). So-called coffin liners were used throughout the nineteenth century and usually consisted of plain wooden boxes (frequently made of pine) meant to encase and protect the often ornate caskets typical of the time. Sometimes these were the original boxes used to ship the caskets, which were typically buried with the caskets out of convenience (Dockall et al. 1996b; Gadus et al. 2002; Habenstein and Lamers 2001; Holloway 1986:74). These boxes were more common after commercially manufactured coffins became widely available (i.e., after the turn of the twentieth century), and they are less common in rural communities where most coffins were built locally and where outer boxes may have been viewed as a waste (Dockall et al. 1996b:160; Gadus et al. 2002:33). Any type of additional protection to coffin burials may increase the PMI over which remains appear to have been interred recently. The gradual breakdown of a coffin allows the infiltration of sediments and the growth of plant roots into the interior (Schultz et al. 2003), both of which can now be in direct contact with remains, and the removal of a barrier to physical disturbance. The collapse of the lid, whether gradual or abrupt, places the remains under the stress of the mass of sediments crushing down and causing warping and fracturing.

Coffins also allow the breakdown of remains in an environment where evidence of this breakdown may be preserved. The repeated waterlogging and drying of bone may cause surface cracking, and acidic dissolution of the mineral component may leave the bone with a friable, chalky texture that easily disintegrates further upon handling (Berryman et al. 1991, 1997; Rogers 2005; Schultz et al. 2003). These two processes may not differ greatly from those undergone by bones buried in direct contact with soil, except bones in the latter environment are much more likely to lose the evidence of these processes as their surfaces exfoliate and the flakes adhere to the soil matrix or break down further to become indistinguishable (macroscopically) from the sediments. A bone recovered from a burial in direct contact with the soil is far more likely to exhibit a pattern of generalized erosion caused by multiple taphonomic processes due to the loss of surface layers (Fernández-Jalvo and Andrews 2003). In some cases, such as those where the burials are adjacent to a high water table (e.g., a bayou), the collapse of the casket and subsequent infill with inundated soil result in skeletal remains that have essentially melded with the wooden casket lid or bottom (e.g., Bond et al. 2002:113), making recovery difficult.

Coffin Wear

The patterned, localized destruction of some portions of a skeleton brought about by contact with a coffin is referred to as *coffin wear* (Rogers 2005; Schultz 2012; Schultz et al. 2003). These changes naturally take a significant passage of time to occur, making their direct observation difficult, so the exact processes are largely theoretical. Once most soft tissue decomposition has occurred, some portions of a skeleton in a coffin naturally come into direct contact with the hard coffin floor. These logically include the posterior portions of several elements, including the occipital portion of the cranium, the vertebral spines/arches, the scapulae, the pelvis, and the limb bones (Berryman et al. 1991, 1997). Settling may be more variable for other elements, and the feet may be better protected due to the presence of leather footwear (see "Boot/Glove Taphonomy" section, above). The portions of the elements in contact with the floor may be attacked preferentially by the acids formed in pooling water within the coffin, leaving them in a weakened state. These portions may lose relatively flat patches of bone that sometimes have a sheared appearance. The most probable portions of the skeleton to develop coffin wear are portions of bones least likely to rotate while settling and to remain with the same portions in contact with the coffin floor throughout burial. Dockall et al. (1996b:212) theorized that vibrations from a nearby train track also may have contributed to coffin wear at the Phillips Memorial Cemetery in Texas through mechanical erosion.

The innominates, scapulae, and femora in particular may be least likely to rock from their initial relative positions due to their positions in the body and their overall morphology. The posterior surfaces of the ilia provide a broad, flat surface for stable positioning, from which it would be difficult to rotate once resting in this aspect. Figure 5.7 illustrates matching areas of coffin wear on the posterior iliac crests of paired innominates; Figure 5.8 illustrates coffin wear along a scapular spine. The greatest degree of cortical erosion is concentrated where these elements would have lain flat against the coffin floor, and the

Figure 5.7 Coffin wear on posterior surfaces of iliac crests; historical context, Massachusetts, USA. Note the flat, sheared appearance of the damaged areas. The scale is in cm.

Figure 5.8 Coffin wear on the posterior scapular spine, historical context, Massachusetts, USA. Note the flat, sheared appearance of the damaged areas. The scale is in cm.

missing portions of bone have a sheared appearance. Similarly, femora present a stable configuration with the condyles providing two widely spaced points on the distal end and the head/neck projecting medially on the proximal end. A great deal of bone erosion or coffin contents settling/disruption must occur for the femur to be easily dislodged from this configuration once these points are resting flat on the coffin floor. Figures 5.9–5.12

Figure 5.9 Coffin wear on posterior surfaces of proximal femora; historical context, Massachusetts, USA. Note the matching areas of missing bone on the posterior proximal ends. The top scale is in cm.

Figure 5.10 Detail of coffin wear on posterior surface of right proximal femur; historical context, Massachusetts, USA. Note the flat, sheared appearance of the damaged areas. The scale is in cm.

illustrate matching areas of coffin wear on paired femora. Damage to the proximal ends (Figures 5.9 and 5.10) appears on the posterior head and trochanter areas. Damage to the distal ends (Figures 5.11 and 5.12) in this example has completely removed the condyles, leaving behind flattened areas of bone. The remaining portions of these femora are in relatively good to excellent condition. Coffin wear can appear on any element that comes to rest on the coffin floor, but it has more time to accrue if that element is not changing its position through further subsidence. While tibias (Figure 5.13) often come to rest on their posterior surfaces and mandibles on their inferior or posterior surfaces (Figure 5.14), crania (Figure 5.15) can come to rest in a variety of orientations and will form coffin wear on those cranial surfaces accordingly.

Schultz et al. (2003:145) illustrated coffin wear on the dorsal surfaces of articulated metacarpals, which did not form while these elements were in contact with the floor but were instead due to the coffin lid coming to rest on top of them. Under some conditions, the decomposing coffin wood may act as sponge for ground water, leaching acid onto bones in contact. Pooling ground water therefore may not be a requirement for coffin wear to form but may speed its formation or increase its extent.

Warping of skeletal remains in coffins is likely caused largely by the same factors as coffin wear (weakening of the bone with moisture/acidic attack, combined with contact with the hard coffin floor), with the increased importance of the mass of sediments

Figure 5.11 Coffin wear on posterior surfaces of distal femora; historical context, Massachusetts, USA. Note the flat, sheared appearance to the damaged condyles. The scale is in cm.

pushing downward on remains in collapsed coffins (Schultz et al. 2003). Warping may be particularly prominent on the cranium (Figure 5.16), given its relatively weak structure relative to its size, combined with the small amount of soft tissue that must decompose prior to the bone coming in direct contact with the coffin floor. Cranial asymmetry caused by warping is also readily apparent, as opposed to warping of some other bones, including

Figure 5.12 Coffin wear on posterior surfaces of a distal right femur; historical context, Massachusetts, USA. Note the flat, sheared appearance to the damaged condyles. The scale is in cm.

Figure 5.13 Coffin wear on posterior surfaces of a proximal tibia; historical context, Massachusetts, USA. Note the flat, sheared appearance. The scale is in cm.

Figure 5.14 Coffin wear on a right posterior mandibular body; cemetery context, Massachusetts, USA. Note the flat, sheared appearance. The scale is in cm.

ribs. Cranial warping may be accompanied by signs of water ring formation and poorer preservation on the portions in contact with the coffin floor, with relatively good preservation, including soft tissue/hair, on the portions farthest from the coffin floor (Figure 5.17). Cranial warping, however, may occur in non-coffin burials as well (pers. obs.).

Figure 5.15 Coffin wear on a right cranial vault, temporal area; cemetery context, Massachusetts, USA. Note the extremely flat, sheared appearance. The scale is in cm.

Staining

Skeletal remains from coffins often become darkly stained, including a chocolate-brown color (Figure 5.18). Schultz et al. (2003:142) noted that this shade and the uniformity of staining are extremely rare in remains of forensic interest. While staining of bone typically occurs in non-coffin burials due to soil contact, the effect is likely intensified in coffin burials due to the highly soluble organic tannins leached from the coffin wood. The same water-pooling effect that is likely instrumental in the formation of coffin wear will also inundate skeletal elements at the bottom of a coffin, with this organic acid leached from the coffin ceiling, walls, and floor. Remains from non-coffin burials in sediments high in decomposing natural organic material may take on a similar coloration, since these organic compounds are produced by a wide variety of plant species.

A variety of species, both hardwood and softwood, were used in wooden coffin construction, with some positive correlation between socioeconomic group and the use of more expensive hardwoods including walnut (*Juglans* spp.), mahogany (*Meliaceae* spp.), cherry (*Prunus* spp.), maple (*Acer* spp.), and chestnut (*Fagacea* spp.). Soft woods were most frequently used, especially pine (*Pinus* spp.) and sometimes poplar (*Populus* spp.) or willow (*Salix* spp.) (Holloway 1986; Pollock 2017; Pollock et al. 2018; Pye 2007). Variations by region have been detected: species identified at the Texas State Cemetery also included bald

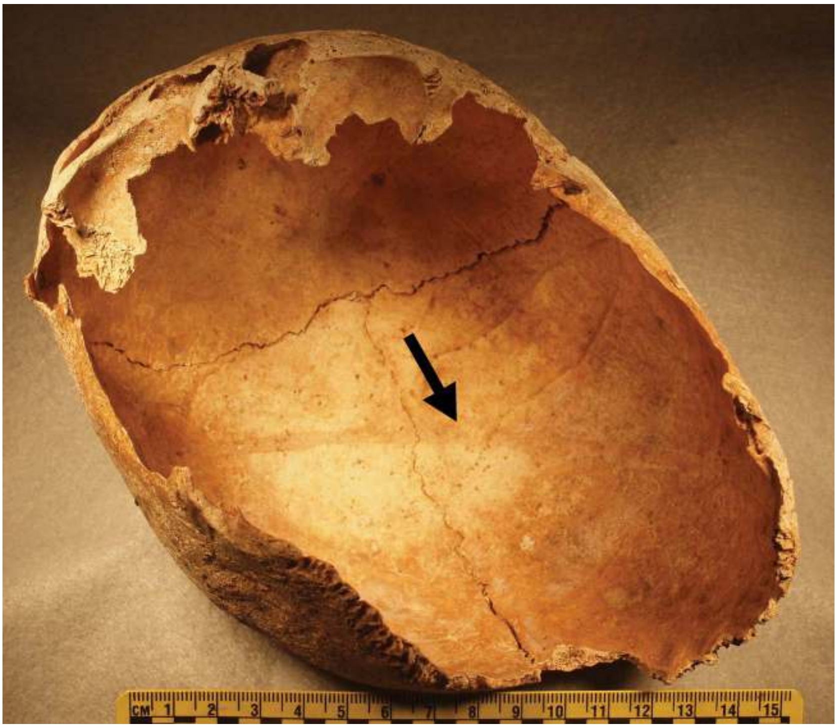

Figure 5.16 Extreme warping on a cranial vault; cemetery context, Massachusetts, USA. Note also the water line (arrow) on the endocranial surface. The scale is in cm.

Figure 5.17 Hair adhering to one side of a cranium; cemetery context, Massachusetts, USA. The scale is in cm.

Figure 5.18 Chocolate-brown staining on an anterior mandible; crypt context, Massachusetts, USA. The scale is in cm.

cypress (*Taxodium distichum*), juniper (*Juniperus* spp.), and spruce (*Picea* spp.) (Dockall et al. 1996a), and the species identified at the Phillips Memorial Cemetery, Texas, USA, included ash (*Fraxinus* spp.) and possibly persimmon (*Diospyros virginiana*) (Dockall et al. 1996b). All of these species potentially can leach tannins into groundwater, not just those darker in color, although in general woods that are lighter in color have fewer tannins (Barbehenn and Constabel 2011). Tannins are also highly concentrated in other parts of plants, including the leaves and nutshells, which is why tannins from natural decomposition easily can stain remains from non-coffin burials (Zelinka and Stone 2011). Schultz et al. (2003) further noted that skeletal remains from above-ground crypt contexts may obtain a uniform orange-brown staining, possibly due to the combination of a lack of groundwater contact and the presence of embalming chemicals.

Signs of Previous Autopsy

Signs of previous alteration at autopsy or subsequent embalming are frequent taphonomic characteristics of remains from modern cemetery burials (Table 5.2 and Chapter 8). Autopsies are routinely performed where there is any question regarding the cause or manner of death of an individual, with large jurisdictions performing thousands of autopsies annually. Sectioning of the cranial vault (Figure 5.19) or other typical autopsy alterations therefore can help indicate the origin of the remains as being likely cemetery, as remains that have received that much processing through a medical examiner/coroner system are unlikely to have gone subsequently missing.

Table 5.2 **Taphonomic Effects, Coffin Remains Sample (n = 68) from Massachusetts, USA, Compared with Previous Research on Cemetery, Autopsied/Embalmed, and Historic Remains**

Characteristics	Berryman et al. (1991, 1997)	Sledzik and Micozzi (1997)	Schultz et al. (2003)	Rogers (2005)	Pokines et al. (2016) and new data	
	Cemetery	Autopsied/ Embalmed	Historic/ Cemetery	Cemetery	n	%
Soft Tissue Preservation						
Embalmed tissue/embalming chemicals	X	X	X	X	4*	5.9
Brain preservation	X				0	0.0
Differential decomposition: trunk better preserved through embalming than appendages	X				0	0.0
Head/facial hair	X	X	X		2	2.9
Cracking/flaking skin (like old paint)	X				0	0.0
Fabric impressions on facial skin	X				0	0.0
Decomposition at pressure points	X				0	0.0
Bone Condition						
Coffin wear at pressure points	X		X		33	48.5
Exfoliation of cortical bone from wetting/drying	X		X	X	26	38.2
Warping/deformation of bones			X		6	8.8
Uniform staining, medium to chocolate-brown (wood coffins)			X		49	72.1
Uniform staining, orange-brown (above-ground crypts)			X		0	0.0
Uniform staining, dark to black (iron coffins)			X		0	0.0
Localized staining, green (Cu), red (Fe), or dark metallic (Hg)			X		9	13.2
Water mineral stains (primarily $CaCO_3$)					8	11.8
=Water ring inside cranial vault					6	21.4**
Localized staining, black (from early historical embalming compounds and decompositional products)		X			0	0.0
Bone preservation state						
Greasy					1	1.5
Degreased, retains some organic sheen					33	48.5

(Continued)

Table 5.2 *(Continued)* **Taphonomic Effects, Coffin Remains Sample (n = 68) from Massachusetts, USA, Compared with Previous Research on Cemetery, Autopsied/Embalmed, and Historic Remains**

	Berryman et al. (1991, 1997)	Sledzik and Micozzi (1997)	Schultz et al. (2003)	Rogers (2005)	Pokines et al. (2016) and new data	
Characteristics	Cemetery	Autopsied/ Embalmed	Historic/ Cemetery	Cemetery	n	%
Degreased, texture is chalky/friable					34	50.0
Cortical erosion					58	85.3
Subaerial weathering (Behrensmeyer 1978)						
WS 1					10	14.7
WS 2					4	5.9
WS 3					1	1.5
Excavation damage					14	20.6
Adhering sediment					53	77.9
Postmortem breakage					66	97.1
Other Taxa						
Plant roots adhering or plant root damage			X		29	42.6
Mold growth on body, especially on skin assoc. with hand and face cosmetics	X				0	0.0
Mold on bone from coffin environment	X				1	1.5
Algae					3	4.4
Gnawing						
Rodent dry-bone					10	14.7
Carnivore					1	1.5
Both					1	1.5
Evidence of Previous Autopsy and Embalming/ Associated Artifacts						
Evidence of previous autopsy: Y-incision of trunk, transverse incision of the scalp	X				0	0.0
Evidence of previous embalming: cribriform plate fracture	X				0	0.0

(Continued)

Table 5.2 ***(Continued)*** **Taphonomic Effects, Coffin Remains Sample (n = 68) from Massachusetts, USA, Compared with Previous Research on Cemetery, Autopsied/Embalmed, and Historic Remains**

	Berryman et al. (1991, 1997)	Sledzik and Micozzi (1997)	Schultz et al. (2003)	Rogers (2005)	Pokines et al. (2016) and new data	
Characteristics	Cemetery	Autopsied/ Embalmed	Historic/ Cemetery	Cemetery	n	%
Evidence of previous autopsy/embalming: sectioning of skull, cutting of ribs and sternum		X			1	1.5
Artifacts: embalming (including eye caps, mouth formers, injector needles, clamps, trocar buttons, sutures, cotton packing, molding wax, eyelid glue, and funerary clothing)	X	X	X	X	0	0.0
Other Artifacts						
Coffin hardware, durable	X		X		6	8.8
Coffin hardware, cardboard/plastic from modern economical caskets				X	0	0.0
Grave markers				X	1	1.5
Grave offerings (including flower pots, flower vases, foil covering, and plastic species identification tags)				X	1	1.5
Period clothing or similar items		X	X		0	0.0

Source: Pokines et al. (2016); used with permission, John Wiley and Sons.

"X" indicates presence of that characteristic noted; not all traits examined for in Pokines et al. (2016) and new data were necessarily examined for in the other research cited.

* Denotes preserved desiccated soft tissue of any kind; previous embalming status is unknown.

** Percentage based upon cases with sufficiently intact cranial vaults (n = 28) only.

Figure 5.19 Autopsy sectioning on a posterior cranial vault, cemetery context, Massachusetts, USA. The scale is in cm.

Signs of Previous Embalming

Embalming has a history spanning at least five millennia worldwide (Mayer 2012; Micozzi 1991) and has many ritual connotations, most arising from providing a vessel for the deceased in the afterlife or to legitimize ancestral claims by being able to produce said ancestors in a recognizable state. A variety of procedures and chemicals have been tried throughout history, with the usual goal of achieving antiseptic conditions to prevent putrefaction, at least long enough for burial rituals. Desiccation of tissues also aided in their preservation, as in deliberate attempts at mummification in ancient Egypt, Peru, Chile, and other cultures. In terms of potential forensic relevance, embalming in the USA became far more prevalent and professionalized during the Civil War, which generated large amounts of bodies, frequently during summer campaigns, and often at a great distance from their ultimate resting place. This factor coincided with a developing railway network that made rapid transportation feasible (Faust 2008). The elaborate, multistate funeral procession of Abraham Lincoln at the war's close also increased the interest in embalming as a standard practice (Faust 2008; Habenstein and Lamers 2001; Mayer 2012; Sledzik and Micozzi 1997). The goal was to have a viewable, natural-looking body that would last throughout funeral proceedings and beyond, with the illusion of incorruptibility extending into the interment period. Multiple chemical and injection methods were tried throughout the ensuing decades (Berryman et al. 1991, 1997), some of which leave behind visible taphonomic alterations or artifacts that may allow the detection of previous embalming (Table 5.2).

Eye caps are thin, oval devices used to hold eyelids shut on cadavers for funerary viewing purposes (Figure 5.20). While other inclusions from embalming may be easier to identify from their size and configuration, eye caps can shrivel in the ground and become highly stained (Figure 5.21). In this degraded state, they might be overlooked if they have been moved from an eye orbit. They also may be mistaken for some other object of artificial or biological origin if not examined closely. Eye caps have been in use for several decades (Dennis Daulton, Dodge Chemical Company, pers. comm.). As listed in manufacturers'

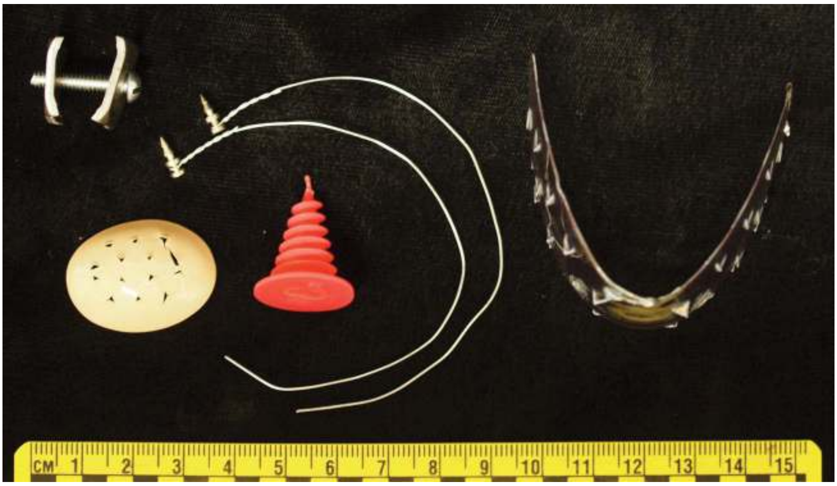

Figure 5.20 Modern (unused) embalming devices that may be recovered with recent remains. Upper left to right: calvaria clamp, eye cap, trocar button, needle barbs, and mouth former. The scale is in cm.

Figure 5.21 Eye cap, (a) interior and (b) exterior; historical context, Massachusetts, USA. Note the warping from burial. The scales are in cm.

catalogs as early as 1903, eye caps were made of wax-coated muslin. At least by 1930, eye caps were being made out of aluminum and plastic/celluloid. Models today are made out of plastic (Mayer 2012).

Additional embalming artifacts, such as *trocar buttons* (Figure 5.20), have been recovered from historical burial excavations dating as early as 1940 (Dockall et al. 1996a:159), and Mayer (2012) noted the use of trocar buttons made of some material as early as the 1920s. Trocar buttons are used to seal the small incisions made during abdominal cavity embalming (Iserson 1994) and sometimes to seal gunshot wounds (Mayer 2012), although sutures can fill both of these roles. Trocar buttons resemble conical plastic screws with a flat top that appears similar to a two-hole button. The depressions are used to assist in the application of the device. One of the authors (JEB) has recovered plastic trocar buttons from burials dating to at least 1955 (Dockall et al. 1996a). A large curved needle and a rubber nipple found in separate burials at the Third New City Cemetery (TNCC) in Houston, Texas, were both hypothesized to represent embalming artifacts (Bond et al. 2002:157). Mouth formers (Figure 5.20), injector needles, sutures, and wax and cotton packing from cosmetic and restorative procedures (including to fill in the space left by donated organs) may be found in burials (Berryman et al. 1991, 1997; Rogers 2005). Mouth formers likely came into use during the 1950s, and some early models were made of aluminum, with plastic ones also known from this early time (Dennis Daulton, Dodge Chemical Company, pers. comm.). Glue is also used frequently for cosmetic purposes (closing eyes and mouths) and to seal suture lines anywhere in the skin, and Mayer (2012) noted the recent use of PVC pipes to replace long bones that have been removed for tissue donation. Other metal devices used to hold skeletal remains together include wires that are anchored into the maxilla and mandible (usually with a barbed point, termed *needle barbs*; Figure 5.20), then twisted together to keep the mouth closed (Mayer 2012). These, of course, would leave visible bone damage and possibly corrosion stains on these skeletal elements, even if the wires were no longer present. Small metal clamps may be used to keep the post-autopsy sectioned calvaria attached to the remainder of the skull and prevent shifting. Schultz (2012:74) provides illustrations of these latter two metal devices recovered from field contexts. *Calvaria clamps* (Figure 5.20) are made of steel and designed to hold together the portions of the cranial vault separated by autopsy sectioning. These have two facing plates attached by a screw. The recovery of any of these items associated with human remains should be a strong indicator of at least historical and more likely recent/modern burial origin of the associated human remains.

Berryman et al. (1991, 1997) noted that the presence of patches of scalp and eyebrow hair, mold on the face, fabric impressions on skin, and cracked, desiccated skin "resembling old paint" is consistent with embalming and hence an original cemetery provenience (Table 5.2). Embalming also can occasionally result in damage to skeletal remains. For example, damage to the cribriform plate may indicate use of cavity embalming of the cranium, in which a trocar is passed through the nostril or the medial corner of the eye and into the cranial cavity, in order to replace gas and fluid with embalming chemicals (Iserson 1994:210; see also Berryman et al. 1991, 1997; Rogers 2005). Modern embalming typically also uses copious amounts of cosmetics, especially where noticeable skin changes have occurred from trauma or early decomposition (Mayer 2012), and traces of these compounds may be found on adhering desiccated tissue.

Massachusetts, USA Forensic Sample and Previous Research into Cemetery Profiles

Pokines et al. (2016) examined a sample (n = 49) cases of cemetery remains received at the Office of the Chief Medical Examiner, Massachusetts (OCME-MA) for overall patterns of taphonomic effects in order to help differentially diagnose them from remains from other sources (Pokines 2018a), and additional case data have been added here to increase this sample size (n = 68). Such remains are common among forensic case work in this jurisdiction (Pokines 2020), although it is likely that other regions of the USA have different patterning among their cemetery remains due to differences in burial environment, coffin types employed (see "Coffin Hardware" section, below), duration of burial, climate, and other factors (Berryman et al. 1991, 1997; Rogers 2005; Schultz et al. 2003). The majority of cases in this Massachusetts sample likely derived from wooden coffins dating to the late 1800s, since this state has a long history of European colonization and cemetery re-use that disturbed earlier graves that lacked permanent markers (Deetz 1977; Dethlefsen and

Table 5.3 Skeletal Part Representation, Coffin Remains Sample (n = 68) from Massachusetts, USA

Skeletal Portions Present	N	%
Single postcranial element only	15	22.1
Multiple postcranial elements only	11	16.2
Partial cranial remains only	26	38.2
Largely complete cranium or skull only	4	5.9
Cranial and postcranial remains	12	17.6
Total	68	100.0

Source: Pokines et al. (2016) and new data. Used with permission, John Wiley and Sons.

Deetz 1966). The taphonomic effects on these remains were compiled relative to those of cemetery, autopsied/embalmed, or historical remains described by previous researchers (Berryman et al. 1991, 1997; Rogers 2005; Schultz et al. 2003; Sledzik and Micozzi 1997) (Table 5.2).

The Massachusetts sample (Pokines et al. 2016 and new data) consisted mostly of isolated skeletal elements, as these tended to get disturbed and brought to the surface in cemeteries singly (Table 5.3). Overall bone preservation fell into the categories of greasy texture (n = 1; 1.5%), degreased but retaining some organic sheen (n = 33; 48.5%), and chalky/friable texture all over (n = 34; 50.0%). Soft tissue preservation was rare in this particular sample (n = 4; 5.9%), as was head/facial hair (n = 2; 2.9%; Figure 5.17). Coffin wear (n = 33; 48.5%), cortical exfoliation (n = 26; 38.2%; Figure 5.22), and uniform staining (n = 49; 72.1%), however, were very common, as were plant root damage (n = 29; 42.6%), cortical erosion (n = 58; 85.3%), adhering sediment (n = 53; 77.9%), and postmortem breakage (n = 66; 97.1%). Localized mineral staining (n = 9; 13.2%) from iron or copper artifacts in contact with the bones (Chapter 12) was uncommon. Whitish mineral buildup consistent with $CaCO_3$ (Figure 5.23) also was uncommon (n = 8; 11.8%); six of these cases (21.4% of the n = 28 with sufficiently intact cranial vaults) were in the form of a distinct ring that had formed inside the vault from repeatedly pooling water (Figures 5.16, 5.23, and 5.24).

Some effects from later surface exposure (Chapters 11 and 20) were present, with algae formation (n = 3; 4.4%), carnivore and/or rodent gnawing (n = 12; 17.7%), and subaerial weathering (n = 15; 22.1%), which mostly reached only to weathering stage (WS) 1 (n = 10), with some WS 2 (n = 4) and WS 3 (n = 1) (Behrensmeyer 1978). Former cemetery remains appear to undergo subaerial weathering rapidly, due in theory to the intervening decades of breakdown of their organic component, leading to their rapid bleaching and cracking (Figures 11.13–11.15, Chapter 11, this volume). Successive layering of taphonomic effects from deposition in different environments is common, and their relative postmortem timing often can be determined (Chapter 20). Coffin hardware was rarely found in association with bones in this sample (n = 6; 8.8%), in keeping with their usual origin as disturbed remains brought piecemeal to the surface. In four out of these six cases with coffin hardware, the remains had been excavated by one of the authors (JTP), thus allowing a greater chance for continued association. The single instance each of a grave marker or offerings being associated with cemetery remains came from a case that also had some coffin hardware (Figure 5.25), the main categories of which are described below.

Figure 5.22 Examples of cortical exfoliation; cemetery contexts, Massachusetts, USA. Top: adult cranial vault; middle: juvenile cranial vault; bottom: juvenile right femur. The scales are in cm.

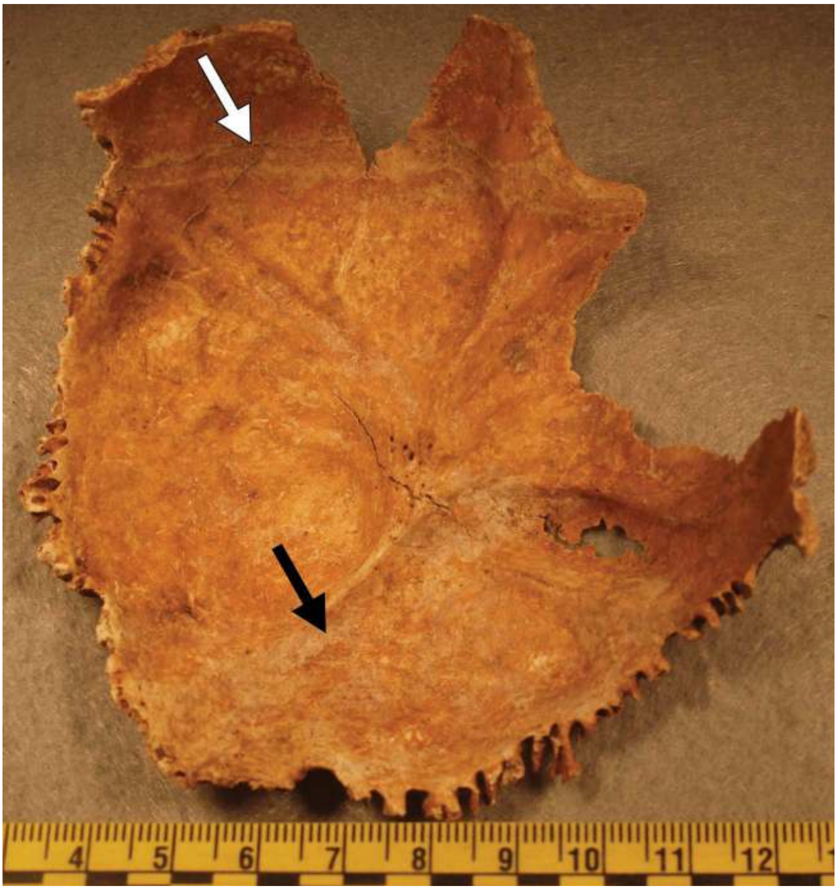

Figure 5.23 Mineral buildup (black arrow) consistent with calcium carbonate on an endocranial surface; cemetery context, Massachusetts, USA. Note also the water line (white arrow). The scale is in cm.

Coffin Hardware

Assuming that no dated headstone (or headstone that can be temporally seriated using stylistic motifs; Dethlefsen and Deetz 1966) is associated, the determination of the temporal and contextual origin of a set of buried remains is often aided by its other associated artifacts (Haglund 2001; Menez 2005). Forensic archaeological analyses and techniques go hand-in-hand with the forensic anthropological analysis of human remains in order to determine their potential origins. Thus, the professional recovery of remains is of paramount importance to their later identification. Even when the wooden portions of a coffin have completely decomposed, remnants of the metal hardware may remain behind in direct association with a buried skeleton (Bell 1990; Davidson 2010; Hacker-Norton and Trinkley 1984; Pye 2007; Springate 2015; Trinkley and Hacker-Norton 1984). Identifying the coffin hardware from the late nineteenth and early twentieth centuries is particularly important, since more recent coffin burials are likely to be better preserved and associated much more clearly with artifacts denoting their recent, yet non-forensic, context. Once a wooden coffin has decomposed, it may not be immediately apparent that the skeletal remains encountered were not buried originally in direct contact with the soil. The remnant

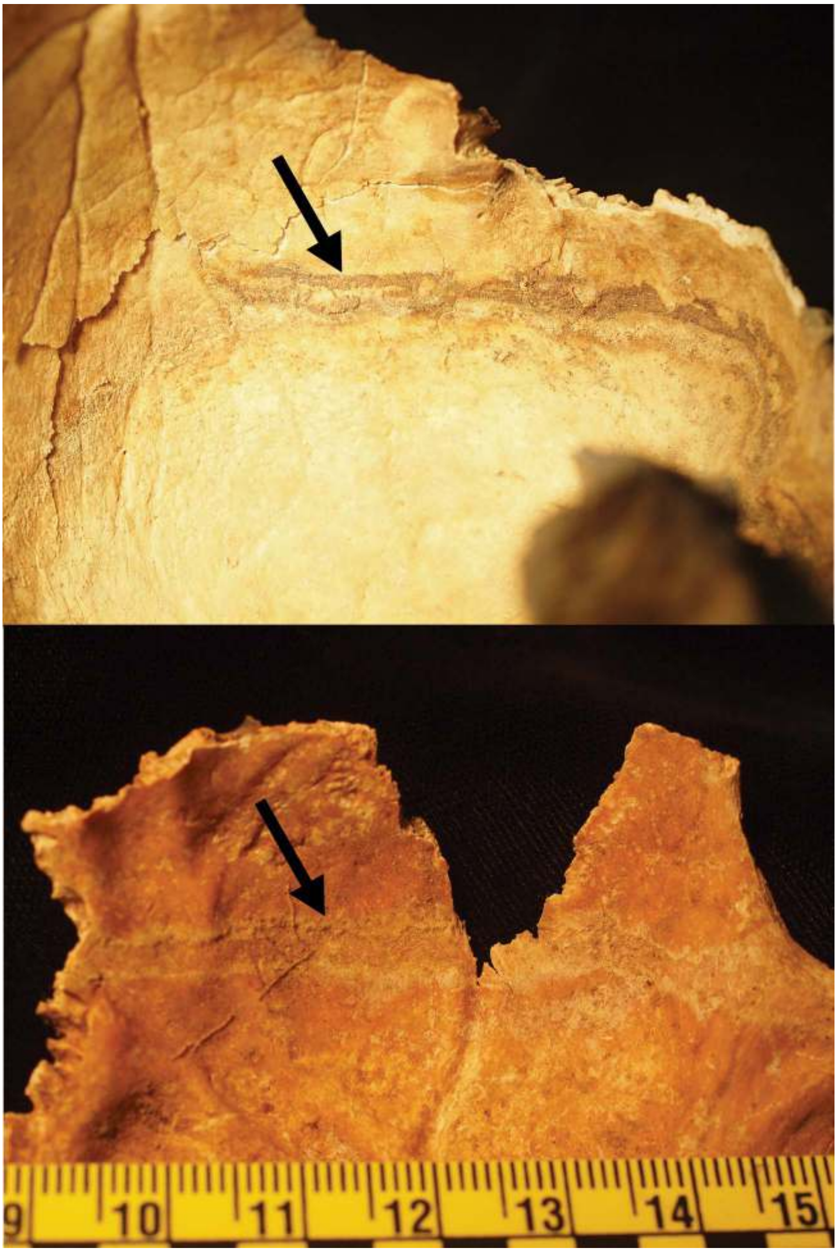

Figure 5.24 Examples of water lines (arrows) on endocranial surfaces; cemetery contexts, Massachusetts, USA. The scale is in cm.

hardware and other artifacts may present vital information that the remains come from an earlier context (Table 5.4). Even with non-coffin burials, organic materials including leather and natural fabrics can persist for decades or longer, especially in waterlogged, anaerobic deposits or arid environments (Janaway 2002). Their remnants, along with the coffin hardware discussed later, may provide useful contextual and temporal data.

Professional headstone carving became a full-time occupation by 1830 in the USA (Dethlefsen and Deetz 1966), making it much easier to date burials from this time onward.

Figure 5.25 Collection of artifacts recovered with cemetery remains, Massachusetts, USA; (a) metal brackets from coffin handles; (b) fragments of glass vases. The scale is in cm.

Mass-produced coffin hardware became common in the USA starting ca. 1850, and the various styles can provide a terminus post quem for dating purposes (Hacker-Norton and Trinkley 1984; Pye 2007; Pye et al. 2004, 2007; Springate 2015). This increase in decoration was part of a trend toward the "beautification of death" (Bell 1990), which also reached the lower classes through the relatively low cost of these items made possible by their mass production. Decorative hardware has even been recovered in large amounts from

Table 5.4 **General Temporal Assignments for Certain Types of Artifacts Found in Burials in the USA**

Artifact Class	Description/Status	Probable Date
Handles	Swing bail	Before 1890
	Extension bar	1911 and later
Caplifters	Absent	Before 1890
	Present	1902 and later
Coffin studs	Absent	Before 1902
	Present	1902 and later
Screws	Present	Before 1900
	Absent	1900 and later
Design motifs	Intricate	Before 1900
	Simple	1900 and later (common after 1920)
Buttons	Bone	Before 1900
	Composite/plastic	1909 and later
Snaps	Absent	Before 1900
	Present	1900 and later

Source: Dockall et al. (1996b:138, Table 34).

paupers' cemeteries, as at the mid-nineteenth century Uxbridge Almshouse Burial Ground in southeastern Massachusetts, which was in use from 1831 to 1872 (Bell 1990), thus spanning this early period of standardization. Seventeen (55%) of the graves examined there included only fragmented wooden coffins constructed with cut iron nails, a few screws, and common brass hinges. Fourteen (45%), however, also contained decorative hardware fittings (see below), and two of these included viewing windows (see "Coffin Viewing Windows" section, below) (Bell 1990:61). Most coffins were hexagonal in overall form. Sixteen of the graves also were given uninscribed marker stones of granite quarry spalls or unmodified fieldstone (Bell 1990:61), and one had an inscribed limestone headstone.

Similarly, the Third New City Cemetery (TNCC), located in Houston's historic "Freedman's Town" and used variously as a pauper's, city (public), and hospital cemetery between 1879 and ca. 1910, yielded a large variety of coffin hardware (defined below). Despite the fact that only 79.6% of 446 possible burial features yielded identifiable human skeletal remains (mostly in very poor condition), excavations at the TNCC yielded 56 types of handles, 14 styles of caplifters, 43 kinds of thumbscrews, 27 types of escutcheons, 31 types of plaques, and 7 additional kinds of ornaments, as well as 14 styles of viewing window (Bond et al. 2002:151, Table 25; F-223–227). In summary, traces of coffin hardware can be recovered even in the extreme circumstances of minimal decorative elaboration, and more elaborate fittings may be common even among burials of paupers, indigents, wards of the state, and other disenfranchised people (see also Dockall et al. 1996a).

Dating of cemetery burials is context dependent. Hacker-Norton and Trinkley (1984) and Dockall et al. (1996b) suggested that the coffin hardware found in rural community cemeteries may not be especially useful in securing a date for burials. In the late nineteenth and early twentieth centuries in particular, conservative tastes, affordability, availability of the latest styles, and wholesale buying of large lots by local funeral vendors may have influenced the coffin and associated hardware styles in rural burials, such that rural communities may have used less expensive, outdated styles relative to their urban counterparts. This may also hold true when relative dating is applied to coffin shape. Hexagonal coffins, along with those tapered to the feet, typically date to an earlier period than rectangular caskets (Bell 1990; Dockall et al. 1996b; Rose and Santeford 1985; although see Earls et al. 1991 for early examples of rectangular caskets). Rural communities, particularly in the southern USA, frequently preferred traditional coffin designs for nostalgic ("like what Father had"; Hacker-Norton and Trinkley 1984:44), financial, logistical, ethnic, and stylistic reasons.

Hacker-Norton and Trinkley (1984), in their study of early coffin hardware in the USA, listed major categories of metal coffin hardware commonly mass-produced by multiple manufacturers. These categories have undergone some modification by other researchers, including Springate (2015), but most of the basic types are in common:

1. *Handles* were attached around the exterior perimeter and used for carrying the coffin and therefore had to be both durable and projecting. Hacker-Norton and Trinkley (1984) listed two categories of handles: bars and swing bails, and Springate (2015:16–18) also included a third category: drop handle. Bar handles are anchored at both ends, swing bails are anchored at both ends but can swing flat against the side of the coffin (a similar design often seen on furniture drawers), and drop handles are ovals anchored centrally on their tops that also can pivot flat against the coffin. All types are affixed to one or more lugs (i.e., the portion that attaches to the coffin). Double lug short bar handles, for example, may consist

Figure 5.26 Example of a metal bracket from a coffin handle, which held one end of a short bar for the pallbearers; historical context, Massachusetts, USA. Remnants of screws are present. The scale is in cm.

of two matching metal alloy lugs (Figure 5.26) holding an outthrust bar, which could have many cross-sectional configurations (including cylindrical, square, octagonal, or even rope-shaped) and could be made of metal or wood. Other configurations include both mounts attached to the same plate (Figure 5.25). The lugs were attached to the sides of the coffin with screws or in some cases nails that were cinched on the inside. Extension bar handles also rely on bars as a carrying mechanism, but in this case, the handles typically run the length and width of the casket, with corner and center lugs attaching the long bars to the walls. Swing bails are typically metal alloy handles that swivel from their attachment points on one or two lugs (Bond et al. 2002). Drop handles have oval or circular grips (Springate 2015:18). Springate (2015:20) noted that sometimes coffins were buried still encased inside their shipping container, and these containers often had non-ornate swing bail handles.

Notwithstanding decorative design, the basic handle type may help determine the age of the coffin burial. Hacker-Norton and Trinkley (1984:44) noted that swing bail handles were the most popular type prior to 1880, while short bar handles were popular between 1880 and 1920. Extension bars were uncommon prior to 1912 but were sold as early as 1877 (Hacker-Norton and Trinkley 1984:44–45). Drop handles were popular in the USA in the 1850s and 1860s (Springate 2015:18).

Three handles per long side was a common configuration, and exceptions include cases where there were fewer pallbearers expected, out of economic necessity, or for child coffins, and the handles for the latter were often smaller overall. At the Texas State Cemetery, the number of handles used on each casket was correlated with handle type and design, ranging in number from four to eight (notably, all were adult burials, and most of the men exhumed were wards of the state at the time of their deaths; Dockall et al. 1996a). At Houston's TNCC, archaeologists

Figure 5.27 Examples of thumb screws, mausoleum context, Massachusetts, USA. The scale is in cm.

recovered one to eight swing bail handles and four to six short bar handles per coffin (Bond et al. 2002:151, Table 25). The regular spacing of these items often is retained in their archaeological context.

2. *Thumbscrews* and *escutchions* (*var.* escutcheons; thumbscrew plates) were used to attach the lid to the rest of the coffin and in this function eventually replaced the nails used previously (Figure 5.27). The thumbscrews, which did not require screwdrivers for application, were threaded through holes in the escutchions and drilled into the wood. These paired items were placed at regular intervals along the lid margin. Several researchers have found a link between the use of thumbscrews and escutchions versus date of interment and particular ethnic groups, suggesting that their occurrence in a burial may be used to provide temporal and cultural context (Bell 1990; Dockall et al. 1996b; Earls et al. 1991; Fox 1984; Orser et al. 1987; Springate 2015; Taylor et al. 1986; Trinkley and Hacker-Norton 1984). Davidson (2000:244) noted that thumbscrews date back to around 1870 and that they became the primary type of screw fastener a decade or so later.
3. *Plates* (*var.* plaques) were attached usually to the center of the coffin lid and engraved/stamped with common memorial phrases or custom-engraved with more personal messages, including the name of the deceased and the date of death (Springate (2015:28).
4. *Caplifters* were essentially knobs attached to moveable portions of the coffin lid in order to raise them during body preparation or for later viewing. Their usage must have been in conjunction with some kind of hinge configuration (Figure 5.28), although plainer coffins may have had hinges and no caplifter. Caplifters and thumbscrews may have been used interchangeably in some cases, and they are commonly associated with base plates or escutchions (Bond et al. 2002). Caplifters were advertised as early as 1877 and became steadily more popular with the increasing popularity of embalming (Hacker-Norton and Trinkley 1984:50), fading out of use in the 1920s (Springate 2015:21).

Figure 5.28 Remnant of a metal coffin hinge; historical context, Massachusetts, USA. The scale is in cm.

Figure 5.29 Remnant of coffin wood with detail of the former extent of a star-shaped metal decorative stud preserved; historical context, Massachusetts, USA. The remaining metal stud is to the right. The corrosion products helped preserve this piece of wood. The scale is in cm.

5. *Decorative studs* were usually stamped from tin and had small tacks soldered to their undersides. These were placed on the outside of the coffin and were employed in some cases to hide nails (Figures 5.29–5.31). Hacker-Norton and Trinkley (1984:47) suggested that studs indicate either a coffin made prior to 1900 or a homemade coffin. Springate (2015:27) also lists *screw caps* as a separate category.

Figure 5.30 Remnant of metal coffin decorative stud; historical context, Massachusetts, USA. The scale is in cm.

These often matched the decorative pattern of coffin studs, except that they were designed with hinged, raised domes to give access to the screws that they were emplaced to obscure. Once corroded, it is possible that the two types would not be distinguishable.

6. *White metal screws* (Figure 5.32) and *tacks* (Figure 5.33) were used for decoration. These could also be employed on the inside of the coffin to attach the lining fabric (Bell 1990). "White metal" refers to multiple types of lead- or tin-based alloys that were frequently silver-plated. Other typical alloys included the metals antimony, copper, nickel, and zinc. The other decorative objects noted earlier were often made of these types of alloys, with handles and hinges also sometimes made of steel or brass for their greater durability. Corrosion of the softer alloys often helped preserve other coffin features, such as fabric impressions (Figure 5.34).

Coffin construction also frequently used iron/steel nails, which can sometimes be used as temporal indicators (Springate 2015). Wire nails were first used in the 1860s and became very popular in the early 1890s in North America; cut nails were more common prior to the 1880s (Priess 1973). However, once mass production of coffins began, finished products could be stored for long periods, while outer boxes or coffin liners, due to their simple nature, were often built at the time of or shortly before burial. Thus, cut and wire nails can

Figure 5.31 Matching metal coffin studs; historical context, Massachusetts, USA. The scale is in cm.

occur in the same feature, particularly in cases where the coffin and the shipping container or outer box were built at different times (Bond et al. 2002:153). In contrast to nails, white metal screws were more popular at the end of the nineteenth century (Dockall et al. 1996b; Earls et al. 1991; Hacker-Norton and Trinkley 1984).

The corrosion products from the nails frequently seeped into the surrounding wood, aiding in the preservation of a small wood fragment while the remainder of the coffin wood decomposed. These wood fragments or even just iron rust stains in the matrix might be all that remains of a plain wooden box coffin lacking in decorative fixtures or an outer box (coffin liner), as in either case, the lid may lack hinges and may have been simply nailed shut (e.g., Dockall et al. 1996b). An example of a coffin wood fragment held together by impregnating rust (Figure 5.35) shows the typical individual irregular shape, and collapse of the coffin during its decomposition might skew any regular pattern to their positioning.

This type of preservation of a small "island" of wood by corrosion products of nails shows up consistently in coffin contexts from historical cemeteries in Massachusetts, but it is not seen on similar nails from contemporaneous houses that have been incorporated into site deposits after their collapse (E. Bell, Massachusetts Historical Commission, pers.

Figure 5.32 Example of a highly corroded screw surrounded by remnant portions of coffin wood; historical context, Massachusetts, USA. The screw head is to the left. The metal oxides have helped preserve the surrounding wood. The scale is in cm.

comm.). This preservational difference may have to do with the immediate burial of the coffin nails in a damp, largely anoxic environment.

Additional functional (versus decorative) coffin hardware types may include metal closures, corner braces, casket rests, hinges, latches, corrugated fasteners, and box hooks (Bond et al. 2002; Springate 2015). Closures were used to attach the sides of the coffin to the headboard, while corner braces held the walls together. Casket rests were metal separators located on the bottom of the coffin/casket, designed to allow removal of the straps used to lower the coffin into the outer box during the burial. Hinges of various sizes and designs were used on coffin and casket lids and on viewing windows and viewing window covers. Latches were sometimes installed on viewing windows to allow the glass to slide open, allowing access to the decedent. Corrugated fasteners consist of corrugated strips of metal used to hold two pieces of wood together and date to the turn of the twentieth century. Box hooks, which are simple U-shaped wire loops used as handles on the outer box, have been recovered from at least one historical cemetery (Bond et al. 2002).

Other Artifacts, Alterations, and Burial Characteristics

Period clothing, even in situations where fabric is not preserved, can give important clues as to original provenience (Table 5.2) (Janaway 2002; Schultz et al. 2003). These items include buttons, which are often preserved after the fabric has decomposed or otherwise been made unidentifiable (e.g., see Fox 1984:12 for a description of a US Army button found in a known Confederate sympathizer's grave). Certain types of buttons, such as those made of bone, porcelain, celluloid, Bakelite, shell, and molded plastic, were used during specific

Figure 5.33 Examples of matching metal coffin tacks; historical context, Massachusetts, USA. These could have been used to attach fabric lining or as exterior decoration. The scale is in cm.

periods and can be used to date burials (Luscomb 1967; Peacock 1973). Snap fasteners typically indicate a post-1900 burial (Rose and Santeford 1985:43). Cufflinks, collar studs, bow ties, or snaps, or lapel, lace, collar, or winding (shroud) pins also may be indicative of historical (i.e., non-forensic) burials (e.g., Bond et al. 2002; Dockall et al. 1996a; Rose and Santeford 1985). Clothing and/or shoes that have been cut in the back may suggest deliberate (cemetery) burial, as this was often done to ease dressing of the corpse (Berryman et al. 1991, 1997; Iserson 1994; Rogers 2005).

Other items that may be found in association with coffin-derived remains include those normally left at cemeteries as offerings (Table 5.2) (Rogers 2005; pers. obs.). These include fragmented flower vases (Figure 5.25), planters, bud holders (Figure 5.36), or small flags. Other personal votive offerings are highly variable (Elliott 1990), but some may have cultural or ethnic significance. For example, ceramics (especially bowls), eating utensils, blue beads, pierced coin jewelry, eggs, broken glass, iron pots, and milk and medicine bottles have been tied to African-American and Southern US folk traditions (Bond et al. 2002; Dockall et al. 1996a,b; Jordan 1982; Rose and Santeford 1985). Glass and ceramics can frequently be dated by composition, design, or manufacture, allowing

Figure 5.34 Remnant fabric preserved by impregnating corrosion products from soft metal coffin decorative motif; historical context, Massachusetts, USA. The scale is in cm.

burials to be dated accordingly (e.g., see Lehner 1980; Santeford 1981). Although it may be difficult to ascertain the origin or purpose of some items found in the grave shaft, they may not have been associated with the deceased person or the mourners at all, but rather with cemetery employees or cemetery surrounds. For example, a liquor bottle was discovered in a grave shaft at the Texas State Cemetery (Dockall et al. 1996a), while fence pickets, fencing wire, and concrete "slump tests" (the last being related to road construction) were recovered from grave fill at the Phillips Memorial Cemetery (Dockall et al. 1996b).

Lining fabrics and various types of cushion fillings may be recovered in historic cemetery burials (Bell 1990; Dockall et al. 1996a; Taylor et al. 1986). For example, at the Philips Memorial Cemetery in La Marque, Texas, five of the caskets excavated included a layer of southern hard pine (*Pinus taeda*) shavings (Dockall et al. 1996b:112; see also Bell 1990; Fox 1984; Parrington and Roberts 1990). The inclusion of pine shavings in proximity to the body may affect preservation due to increased acidity in the casket's microenvironment (see "Staining" and "Acidic Soil Corrosion" sections, above). Evans (1963) suggested that bodies buried in coffins with wood shavings decomposed faster than those buried in the soil, because the temperature rose due to moisture in the wood shavings and subsequent

Figure 5.35 Examples of highly corroded iron screws surrounded by remnant portions of coffin wood; historical context, Massachusetts, USA. The iron oxide has helped preserve the surrounding wood. The scale is in cm.

Figure 5.36 Examples of (recent) plastic bud holders that may accompany cemetery remains. The scale is in cm.

fermentation of the organic material. Other organic materials, such as hay or grass, may have been used to line caskets as well (Bell 1990).

Dental attrition and style of restorations are also an important source of information in determining the burial era of a body (Rogers 2005). Dental attrition in cultures where the diet was largely derived from stone-ground grain, with constant mastication of its inherent fine grit, was much more rapid than in the modern era with highly processed foods mostly lacking this inclusion (Brothwell 1981).

Lifesaving devices (or remnants thereof) may also be found in association with coffin burials. These devices, designed to warn the living that a buried individual was still alive, became fashionable in the Victorian era, with the earliest such device patented in 1843 (Habenstein and Lamers 2001; Springate 2015). At a time when modern medicine was in its infancy and death from communicable disease was common, the possibility of being buried alive seemed plausible (Tebb and Vollum 1905). Variants included bells or whistles that sounded above ground, speaking tubes running to the surface, electrical alarms, flags, and lamps that signaled the living. A possible accoutrement of a lifesaving device was found in an iron coffin from the Texas State Cemetery, in the form of a diamond-shaped hole in the lid of the coffin at approximately the area of the right hand (Dockall et al. 1996a). Another possible lifesaving device remnant (a circular rubber ring in the vicinity of a hole in the casket that correlated to the location of the hands) was found with a coffin from the TNCC in Houston, Texas (Bond et al. 2002:F-218). The increasingly common practice of embalming bodies throughout this period gradually allayed this fear, and these items were largely discontinued.

In some cases, characteristics of the burial may assist in determining its origin (e.g., clandestine versus cemetery). In many Christian societies, cemetery burials are oriented with the head to the west (but see Fox 1984:43 for an example of an accidental juxtaposition of an infant in a rectangular coffin). This practice is tied to the idea that the dead will rise and face the second coming of Jesus Christ on Judgment Day (Jordan 1982:30; Yalom 2008:12). However, this rule does not always hold, as Hispanic burial grounds in the USA frequently have many burial axes; an east-west axis holds no particular meaning in Hispanic culture (Jordan 1982:70). Upside-down burials have been linked to suicides, deserters, witches, and the morally reprehensible (Jordan 1982; Robertson 1984:155, cited in Taylor et al. 1986:42), while north-south oriented burials have been linked to criminals and suicides (Jordan 1982). In addition, folk tradition holds that husbands are buried to the south (i.e., at the right hand) of their wives, mimicking the positions of the bride and groom at the wedding altar (Fox 1984; Jordan 1982); thus, the sex of individuals, as determined via anthropological analysis, of two side-by-side burials should be considered in relation to this tradition (although see Fox 1984:40 for a historical exception to this rule). High rates of infant mortality prior to the mid-twentieth century may have resulted in a large number of fetal and infant remains in unmarked historical cemeteries, yielding another indicator that the remains in question may not be of forensic interest. In some cases, these infant burials may be clustered in a separate section of a family or local cemetery (Fox 1984:45).

Spatial patterning of multiple graves also may be an indicator of burial origin. Modern commercial cemeteries sell plots in orderly rows, but this type of rigid organization did not always exist. Southern folk cemeteries and family cemeteries frequently may have overlapping burials, clusters of graves, or staggered rows, while early church cemeteries typically show more linear organization (Deetz 1977; Jordan 1982; Taylor et al. 1986). These types of burial characteristics may be useful in determining burial origin when human remains are encountered in an unknown context, as early Colonial, folk, and small family cemeteries may have become lost over time, with headstones removed for use in local building projects or to make way for construction (prior to laws forbidding such activities; Baker et al. 2000; Fox 1984; Gadus et al. 2002; Taylor et al. 1986). In other cases, grave markers may have been made of wood, bricks, shells, or groupings of natural, unmarked stones. Wooden markers may decompose entirely or be carried away by collectors, and the bricks, shells, or stones may become scattered over time or overlooked by the casual observer as natural occurrences (Fox 1984:31, 37, 51; Gadus et al. 2002; Jordan 1982; Taylor et al. 1986; Yalom 2008:129). In still other cases, graves may have been left unmarked deliberately for socioeconomic, status, or religious reasons, as in possible slave burials at the Varnell Cemetery in Texas (Gadus et al. 2002:25; see also Yalom 2008:34, 115), early missionary burials of converted Native Americans, and early Quaker burials (i.e., predating 1850) (Yalom 2008:11).

Spatial organization may vary widely depending on the type and use dates of a given cemetery. In the 1600s and early 1700s, church cemeteries in the northeastern part of the USA were often overcrowded, with later burials intruding on earlier ones and with little regard for tracking each individual buried there. Excavations in these areas may reveal haphazard or erratic burial spacing. Family plots with individual burials became customary in the late 1700s, while the tradition of linear, organized, permanent burial plots in formally designated cemeteries did not take hold until the early 1800s (Deetz 1977). Small family cemeteries persisted in rural areas well into the late 1800s and early 1900s (Fox 1984).

On a larger scale, the larger landscape (including relative location) should also be considered when assessing the origin of buried human remains. Cemeteries are frequently found on hilltops, for example, and certain types of plants have historically been associated with cemeteries (including evergreens, irises, azaleas, and willows; Gadus et al. 2002:29; Jordan 1982; Taylor et al. 1986:14; Yalom 2008:113, 118, 135). Green spaces may persist next to public buildings and facilities for decades without any particular known reason; such suspicions can often be verified through tax and property records (Rogers 2005). Remnants of wooden, stone, or wrought iron fences may also be found on the margins of many "forgotten" cemeteries (Fox 1984; Taylor et al. 1986).

In some cases, the type of remains found, in connection with current land usage, may be helpful in ascertaining forensic significance. As Rogers (2005) pointed out, hospitals historically may have used particular locations within their cemeteries to dispose of amputated limbs, so a discovery of limbs from more than one person may be related to medical waste rather than homicide.

Coffin Viewing Windows

One particular type of coffin popular in the latter half of the nineteenth and early twentieth century featured a window for formal viewing with the coffin lid closed, allowing mourners to view the deceased individual's face. Viewing windows came in a variety of sizes and shapes (e.g., 10 styles were discovered at Houston's TNCC alone; Bond et al. 2002), and some were large enough to allow a view of a portion of the torso as well. Taylor et al. (1986:45) noted that viewing windows in infant coffins typically went the full length of the box, or nearly so. Viewing windows appeared as early as 1848 (Habenstein and Lamers 2001), were popular throughout the Victorian Era, and persisted into the early twentieth century. Springate (2015:29) noted that their use in the Southeastern USA declined after embalming became more popular and viewing could be accomplished with the coffin open. These windows were commonly made of plate glass (Bell 1990) due to the stresses that would be exerted by grave fill.

Once this glass structure is breached, however, highly localized destructive taphonomic forces can be introduced to this portion of the remains (Owsley and Compton 1997). The glass allows condensation to collect on its inner surface; in fact, this phenomenon can often be viewed during the excavation process, as small amounts of air are trapped under the glass fragments. A particular taphonomic pattern of destruction of the skeletal elements under the window with relatively good preservation of the remaining elements may result. Following decomposition of the soft tissues, the trapped moisture, accompanied by the collapse and fracturing of the glass, can result in a crushing of the delicate bones of the upper body, including the sternum, ribs, vertebrae, and facial bones. This effect is compounded by the relatively thin cortex and high amount of cancellous tissue in the bones of the torso. These bones may all but disappear over decades of burial, leaving only a residue of organic material resembling bone meal (Bond et al. 2002; Dockall et al. 1996a; pers. obs.). Fragments of plate glass will likely be found near their original position and in association with the skeletal remains, assuming sufficient excavation provenience controls are maintained.

Iron Coffins

Iron coffins present a distinct burial environment due to their durability as compared to wooden coffins and their greater ability to prevent other taphonomic agents (plant root invasion, fossorial vertebrates, acidic soil corrosion, etc.) from reaching skeletal remains. This artificial environment may be similar to the effects of burials in wet, iron-pan forming soils that have allowed excellent long-term preservation of organic materials in burial mounds due to the creation of anaerobic conditions (Breuning-Madsen et al. 2001). Owsley and Compton (1997) examined the preservation typical to cast iron coffin burials, which first came into widespread use with a mass-produced model introduced in 1848 (Springate 2015:38–39). These were replaced by sheet metal models in later years, with the cast iron models produced until around 1880. These iron models, curiously, usually contained glass-viewing windows, thus at once providing a weak point in the structure that could allow the sudden introduction of multiple taphonomic agencies to a localized portion of the remains despite the overall highly protective design.

Owsley and Compton (1997) noted the overall excellent preservation of soft tissue and degradable artifacts (clothing and other personal items) by cast iron coffins. This is likely due to a combination of embalming and the anoxic microenvironment of the coffin, as seals were used when joining the lid to the base. The sealant used frequently was a mixture of ground lead and oil (Owsley and Compton 1997:523), which had the dual purpose of preserving the remains for viewing and preventing the venting of decomposition gases. The potential for excellent preservation makes burials of this type extremely problematic, as the remains may be mistaken for those of forensic interest. Once the coffin has been breached, often through the viewing window, the typical processes of decomposition set in. Owsley and Compton (1997:524) and Schultz et al. (2003:142) also noted that the remains contained within are often stained dark/black, likely from mineral oxide leaching from the coffin. They do not note iron oxide (red rust) staining as typical.

Conclusions

No single suite of taphonomic characteristics is found on buried skeletal remains brought to or excavated by forensic anthropologists, since the circumstances of burial vary so widely in context and duration. These may include recent clandestine burials, modern coffin burials, historical or archaeological non-coffin burials, or burials where wooden coffins decomposed early during the postmortem process. Similarly, wide differences in soil conditions and biological activity also greatly affect the ultimate state in which remains are recovered. To determine the ultimate origin of a given set of remains (and with it, jurisdiction by a medical examiner's office or State archaeological agency), the accompanying burial context, including artifactual evidence, is crucial and cannot be disregarded. Toward this goal, forensic archaeological field procedures and artifact analysis may play just as important a role as the taphonomic analysis of the skeletal remains.

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References

Andrews, P. (1995) Experiments in taphonomy. *Journal of Archaeological Science* 22:147–153.

Andrews, P., and J. Cook (1985) Natural modifications to bones in a temperate setting. *Man* 20:675–691.

Armour-Chelu, M., and P. Andrews (1994) Some effects of bioturbation by earthworms (Oligochaeta) on archaeological sites. *Journal of Archaeological Science* 21:433–443.

Armour-Chelu, M., and P. Andrews (1996) Surface modification of bone from Overton Down, Wiltshire. In *The Experimental Earthwork Project 1960–1992* ed. by M. Bell, P. J. Fowler and S. W. Hillson, pp. 178–185. Council for British Archaeology, Bootham, UK.

Bais, H. P., T. L. Weir, L. G. Perry, S. Gilroy, and J. M. Vivanco (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology* 57:233–266.

Baker, J. E., M. D. Freeman, and M. E. Blake (2000) *Historical Research and Archeological Investigations at the Williamson Creek Cemetery, 41TV1684, Travis County, Texas*. Technical Reports, Number 49, Prewitt and Associates, Inc., Austin, TX.

Barbehenn, R. V., and C. P. Constabel (2011) Tannins in plant-herbivore interactions. *Phytochemistry* 72(13):1551–1565.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Paleobiology* 4(2):150–162.

Bell, E. L. (1990) The historical archaeology of mortuary behavior: Coffin hardware from Uxbridge, Massachusetts. *Historical Archaeology* 24:54–78.

Benninger, L. A., D. O. Carter, and S. L. Forbes (2008) The biochemical alteration of soil beneath a decomposing carcass. *Forensic Science International* 180:70–75.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1991) Recognition of cemetery remains in the forensic setting. *Journal of Forensic Sciences* 36(1):230–237.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1997) Recognition of cemetery remains in the forensic setting. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 165–170. CRC Press, Boca Raton, FL.

Bocek, B. (1992) The Jasper Ridge reexcavation experiment: Rates of artifact mixing by rodents. *American Antiquity* 57(2):261–269.

Bond, C. L., S. D. Hoyt, and E. Baxter (2002) *Archaeological Investigation Report Allen Parkway Village, 41HR886 Houston, Harris County, Texas* ed. by E. R. Foster and L. A. Nance. PBS&J, Inc., Austin, TX.

Breuning-Madsen, H., M. K. Holst, and M. Rasmussen (2001) The chemical environment in a burial mound shortly after construction—An archaeological-pedological experiment. *Journal of Archaeological Science* 28(7):691–697.

Brothwell, D. R. (1981) *Digging up Bones* (3rd ed.). Cornell University Press, Ithaca, NY.

Brothwell, D. R., B. Gottlieb, and D. Liversage (1990) Radiographic and forensic aspects of the female Huldremose body. *Journal of Danish Archaeology* 9(1):157–178.

Casallas, D. A., and M. K. Moore (2012) High soil acidity associated with near complete mineral dissolution of recently buried human remains. *Proceedings of the American Academy of Forensic Sciences* 18:400–401.

Child, A. M. (1995) Microbial taphonomy of archaeological bone. *Studies in Conservation* 40:19–30.

Christensen, A. M., and S. W. Myers (2011) Macroscopic observations of the effects of varying fresh water pH on bone. *Journal of Forensic Sciences* 56(2):475–479.

Crow, P. (2008) Mineral weathering in forest soils and its relevance to the preservation of the buried archaeological resource. *Journal of Archaeological Science* 35(8):2262–2273.

D'Errico, F., and P. Villa (1997) Holes and grooves: The contribution of microscopy and taphonomy to the problem of art origins. *Journal of Human Evolution* 33(1):1–31.

Damann, F. E. (2010) *Human Decomposition Ecology at the University of Tennessee Anthropology Research Center*. Ph.D. Dissertation, University of Tennessee, Knoxville, TN.

Davidson, J. M. (2000) The development of Freedman's Cemetery. In *Freedman's Cemetery: A Legacy of a Pioneer Black Community in Dallas, Texas* (Vol. 2), ed. by D. E. Peter, M. Prior, M. M. Green, and V. G. Clow, pp. 233–407. Report No. 21, Environmental Affairs Division, Archeology Studies Program, Texas Department of Transportation. Special Publication No. 6, Geo-Marine, Inc., Plano, TX.

Davidson, J. M. (2010) Keeping the Devil at bay: The shoe on the coffin lid and other grave charms in 19th and early 20th Century America. *International Journal of Historical Archaeology* 14(4):614–649.

Davidson, J. M. (2012) "They laid planks 'crost the coffins": The African origin of grave vaulting in the United States. *International Journal of Historical Archaeology* 16(1):86–134.

Deetz, J. (1977) *In Small Things Forgotten: The Archeology of Early American Life*. Anchor Press/Doubleday, Garden City, NY.

De-la-Peña, C., V. D. V. Badri, Z. Lei, B. S. Watson, M. M. Branda, M. C. Silva-Filho, L. W. Sumner, and J. M. Vivanco (2010) Root secretion of defense-related proteins is development-dependent and correlated with flowering time. *The Journal of Biological Chemistry* 285(40):30654–30665.

Dethlefsen, E. N., and J. Deetz (1966) Death's heads, cherubs, and willow trees: Experimental archaeology in Colonial cemeteries. *American Antiquity* 31(4):502–510.

Dockall, H. D., D. K. Boyd, M. D. Freeman, R. L. Garza, K. E. Stork, and J. E. Baker (1996a) *Confederate Veterans at Rest: Archaeological and Bioarchaeological Investigations at the Texas State Cemetery, Travis County, Texas*. Reports of Investigations No. 107. Prewitt and Associates, Inc., Austin, TX.

Dockall, H. D., J. F. Powell, and D. G. Steele (1996b) *Home Hereafter: An Archaeological and Bioarchaeological Analysis of an Historic African-American Cemetery (41GV125)*. Reports of Investigations No. 5. Center for Environmental Archaeology, Texas A&M University, College Station, TX.

Duhig, C. (2003) Non-forensic remains: The use of forensic archaeology, anthropology, and burial taphonomy. *Science and Justice* 43(4):211–214.

Earls, A. C., C. R. Lintz, G. W. Gill, P. L. O'Neill, and W. N. Trierweiler (1991) *Investigations of Historic Cemeteries at O. H. Ivie Reservoir, Coleman, Concho, and Runnels Counties, Texas*. Mariah Technical Report No. 403. Mariah Associates, Inc., Austin, TX.

Elliott, J. R. (1990) Funerary artifacts in contemporary America. *Death Studies* 14(6):601–612.

Evans, W. E. D. (1963) *The Chemistry of Death*. Charles C Thomas, Springfield, IL.

Evershed, R. P. (1992) Chemical composition of a bog body adipocere. *Archaeometry* 34(2):253–265.

Faust, D. G. (2008) *This Republic of Suffering: Death and the American Civil War.* Vintage, New York.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Fiedler, S., F. Buegger, B. Klaubert, K. Zipp, R. Dohrmann, M. Witteyer, M. Zarei, and M. Graw (2009) Adipocere withstands 1600 years of fluctuating groundwater levels in soil. *Journal of Archaeological Science* 36(7):1328–1333.

Fisher, J. W. (1995) Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory* 2(1):7–68.

Fitzpatrick, R. W. (2008) Nature, distribution, and origin of soil materials in the forensic comparison of soils. In *Soil Analysis in Forensic Taphonomy* ed. by M. Tibbett and D. O. Carter, pp. 1–28. CRC Press, Boca Raton, FL.

Forbes, S. L., B. H. Stuart, and B. B. Dent (2005) The effect of the method of burial on adipocere formation. *Forensic Science International* 154(1):44–52.

Fox, A. A. (1984) *A Study of Five Historic Cemeteries at Choke Canyon Reservoir, Live Oak and McMullen Counties, Texas.* Choke Canyon Series Vol. 9. Center for Archaeological Research, University of Texas, San Antonio, TX.

Gabet, E. J., O. J. Reichman, and E. W. Seabloom (2003) The effects of bioturbation on soil processes and sediment transport. *Annual Review of Earth and Planetary Sciences* 31(1):249–273.

Gadus, E. F., J. E. Baker, and A. E. Dase (2002) *A Mother Left to Mourn, Archeological and Historical Investigations at a Nineteenth-Century Family Cemetery at the Jewett Mine*. Reports of Investigations, Number 136. Prewitt and Associates, Inc., Austin, TX.

Galloway, A., W. H. Birkby, A. M. Jones, T. E. Henry, and B. O. Parks (1989) Decay rates of human remains in an arid environment. *Journal of Forensic Sciences* 34(3):607–616.

Garman, J. C. (1996) This church is for the living: An assessment of archaeological standards for the removal of cemeteries in Rhode Island and Massachusetts. *Northeast Historical Archaeology* 25(1):1–12.

Gill-King, H. (1997) Chemical and ultrastructural aspects of decomposition. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 93–108. CRC Press, Boca Raton, FL.

Gordon, C. G., and J. E. Buikstra (1981) Soil pH, bone preservation, and sampling bias at mortuary sites. *American Antiquity* 46(3):566–571.

Gostner, P., P. Pernter, G. Bonatti, A. Graefen, and A. R. Zink (2011) New radiological insights into the life and death of the Tyrolean Iceman. *Journal of Archaeological Science* 38:3425–3431.

Habenstein, R. W., and W. M. Lamers (2001) *The History of American Funeral Directing* (5th ed.). Burton and Mayer, Brookfield, WI.

Hacker-Norton, D., and M. Trinkley (1984) *Remember Man Thou Art Dust: Coffin Hardware of the Early Twentieth Century.* Chicora Foundation Research Series 2, Columbia, SC.

Hadingham, E. (1994) The mummies of Xianjiang. Electronic document, https://www.discovermagazine.com/planet-earth/the-mummies-of-xinjiang, accessed 15 March 2021.

Haglund, W. D. (2001) Archaeology and forensic death investigations. *Historical Archaeology* 35(1):26–34.

Haglund, W. D. (2002) Recent mass graves, an introduction. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 243–261. CRC Press, Boca Raton, FL.

Haglund, W. D., M. Connor and D. D. Scott (2002) The effect of cultivation on buried human remains. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 133–150. CRC Press, Boca Raton, FL.

Haglund, W. D. (1991) *Applications of Taphonomic Models to Forensic Investigations*. Ph.D. Dissertation, University of Washington, Seattle, WA.

Hedges, R. E. M., A. R. Millard, and A. W. G. Pike (1995) Measurements and relationships of diagenetic alteration of bone from three archaeological sites. *Journal of Archaeological Science* 22(2):201–209.

Henderson, J. (1987) Factors determining the state of preservation of human remains. In *Death, Decay and Reconstruction: Approaches to Archaeology and Forensic Science* ed. by A. Boddington, A. N. Garland, and R. C. Janaway, pp. 43–54. Manchester University Press, Manchester, UK.

Hochrein, M. J. (2002) An autopsy of the grave: Recognizing, collecting, and preserving forensic geotaphonomic evidence. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 45–70. CRC Press, Boca Raton, FL.

Holloway, R. G. (1986) Appendix B: Analysis of wood remains from the Morgan Chapel Cemetery, 41 BP 200. In *Archaeological Investigations at Morgan Chapel Cemetery (41 BP 200), A Historic Cemetery in Bastrop County, Texas* ed. by A. J. Taylor, A. A. Fox, and I. W. Cox, pp. 73–76. Archaeological Survey Report No. 146. Center for Archaeological Research, The University of Texas at San Antonio, San Antonio, TX.

Hughes, C., C. Juarez, L. Zephro, G. Fowler, and S. Chacon (2012) Past or present? Differentiating California prehistoric Native American remains from forensic cases: An empirical approach. *International Journal of Osteoarchaeology* 22(1):110–118.

Iserson, K. V. (1994) *Death to Dust: What Happens to Dead Bodies?* Galen Press, Tucson, AZ.

Janaway, R. C. (2002) Degradation of clothing and other dress materials associated with buried bodies of archaeological and forensic interest. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 379–402. CRC Press, Boca Raton, FL.

Janaway, R. C. (2008) The decomposition of materials associated with buried cadavers. In *Soil Analysis in Forensic Taphonomy* ed. by M. Tibbett and D. O. Carter, pp. 153–201. CRC Press, Boca Raton, FL.

Jans, M. M. E., H. Kars, C. M. Nielsen-Marsh, C. I. Smith, A. G. Nord, P. Arthur, and N. Earl (2002) In situ preservation of archaeological bone: A histological study within a multidisciplinary approach. *Archaeometry* 44(3):343–352.

Johnson, D. L. (1989) Subsurface stone lines, stone zones, artifact-manuport layers, and biomantles produced by bioturbation via pocket gophers (*Thomomys bottae*). *American Antiquity* 54(2):370–389.

Jordan, T. G. (1982) *Texas Graveyards: A Cultural Legacy*. University of Texas Press, Austin, TX.

Kahana, T., J. Almog, J. Levy, E. Shmeltzer, Y. Spier, and J. Hiss (1999) Marine taphonomy: Adipocere formation in a series of bodies recovered from a single shipwreck. *Journal of Forensic Sciences* 44(5):897–901.

Kollmorgen Instruments Corporation (1994) *Munsell® Soil Color Charts* (revised edn.). Kollmorgen Instruments Corporation, New Windsor, NY.

Lehner, L. (1980) *Complete Book of American Kitchen and Dinner Wares*. Wallace-Homestead, Des Moines, IA.

Luscomb, S. C. (1967) *The Collector's Encyclopedia of Buttons*. Bonanza Books, New York.

Lyman, R. L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

Matthiesen, H., A. M. H. Eriksen, J. Hollesen, and M. Collins (2021) Bone degradation at five Arctic archaeological sites: Quantifying the importance of burial environment and bone characteristics. *Journal of Archaeological Science* 125:105296. DOI: 10.1016/j.jas.2020.105296.

Mayer, R. G. (2012) *Embalming: History, Theory, and Practice* (5th ed.). McGraw-Hill, New York.

Mayne, R. H. (2013) *Geochemistry of the Soil and its Effect on Bone*. BSc Dissertation, Bournemouth University, Bournemouth, UK.

McCraw, K. (2014) *Bone Preservation in an Archaeological Burial Assemblage: The Effects of Time, Soil pH, Age, and Sex*. M.S. Thesis, Boston University School of Medicine, Boston.

Menez, L. L. (2005) The place of the forensic archaeologist at a crime scene involving a buried body. *Forensic Science International* 152(2–3):311–315.

Mickleburgh, H. L., and D. J. Wescott (2018) Controlled experimental observations on joint disarticulation and bone displacement of a human body in an open pit: Implications for funerary archaeology. *Journal of Archaeological Science: Reports* 20(1):158–167.

Micozzi, M. S. (1991) *Postmortem Change in Human and Animal Remains: A Systematic Approach*. Charles C Thomas, Springfield, IL.

Micozzi, M. S. (1997) Frozen environments and soft tissue preservation. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 171–180. CRC Press, Boca Raton, FL.

Mitford, J. (1998) *The American Way of Death Revisited*. Vintage Books, New York.

Morlan, R. E. (1984) Toward the definition of criteria for the recognition of artificial bone alterations. *Quaternary Research* 22(2):160–171.

Nawrocki, S. P. (1995) Taphonomic processes in historic cemeteries. In *Bodies of Evidence: Reconstructing History through Skeletal Analysis* ed. by A. Grauer, pp. 49–66. Wiley-Liss, New York.

Newcomb, A. M. (2015) *Observations of the Impacts of Mechanical Plowing on Buried Remains in Forensic and Archaeological Contexts*. M.S. Thesis, Boston University School of Medicine, Boston.

Newcomb, A. M., J. T. Pokines, and T. E. Moore (2017) Taphonomic effects of mechanical plowing on buried juvenile remains. *Journal of Forensic Sciences* 62(1):67–73.

Nicholson, R. A. (1996) Bone degradation, burial medium and species representation: Debunking the myths, an experiment-based approach. *Journal of Archaeological Science* 23(4):513–533.

Nicholson, R. A. (1998) Bone degradation in a compost heap. *Journal of Archaeological Science* 25(5):393–403.

Nielsen-Marsh, C. M., and R. E. M. Hedges (2000) Patterns of diagenesis in bone I: The effects of site environments. *Journal of Archaeological Science* 27(12):1139–1150.

O'Brien, T. G., and A. C. Kuehner (2007) Waxing grave about adipocere: Soft tissue change in an aquatic context. *Journal of Forensic Sciences* 52(2):294–301.

Odell, G. H., and F. Cowan (1987) Estimating tillage effects on artifact distributions. *American Antiquity* 52(3):456–484.

Orser, C. E., A. M. Nekola, and J. L. Roark (1987) *Exploring the Rustic Life: Multidisciplinary Research at Millwood Plantation, a Large Piedmont Plantation in Abbeville County, South Carolina, and Elbert County, Georgia*. Mid-American Research Center, Loyola University of Chicago, Chicago.

Owsley, D. W., and B. E. Compton (1997) Preservation in late 19th Century iron coffin burials. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 511–526. CRC Press, Boca Raton, FL.

Parrington, M., and D. G. Roberts (1990) Demographic, cultural, and bioanthropological aspects of a nineteenth-century free Black population in Philadelphia. In *A Life in Science: Papers in Honor of J. Lawrence Angel* ed. by J. E. Buikstra, pp. 138–170. Center for American Archeology, Kampsville, IL.

Peacock, P. (1973) *Antique Buttons: Their History and How to Collect Them*. Drake Publishers, New York.

Pilloud, M. A., M. S. Megyesi, M. Truffer, and D. Congram (2016) The taphonomy of human remains in a glacial environment. *Forensic Science International* 261(1):161.e1–161.e8.

Pokines, J. T. (2009) Forensic recoveries of U.S. war dead and the effects of taphonomy and other site-altering processes. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 141–154. Prentice Hall, Upper Saddle River, NJ.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T. (2018a) Differential diagnosis of the taphonomic histories of common types of forensic osseous remains. *Journal of Forensic Identification* 68(1):87–145.

Pokines, J. T. (2018b) Two cases of dendrochronology used to corroborate a forensic postmortem interval. *Journal of Forensic Identification* 68(4):457–465.

Pokines, J. T. (2020) The case of the… cases: The flow of the ordinary into a medical examiner's office. In *Case Studies in Forensic Anthropology: Bonified Skeletons* ed. by H. Garvin and N. Langley, pp. 291–302. CRC Press, Boca Raton, FL.

Pokines, J. T., and J. C. Kerbis Peterhans (2007) Spotted hyena (*Crocuta crocuta*) den use and taphonomy in the Masai Mara National Reserve, Kenya. *Journal of Archaeological Science* 34(11):1914–1931.

Pokines, J. T., and K. Springer (2016) A case of localized corrosion on bone caused by chemical contact. *Journal of Forensic Identification* 66(3):173–186.

Pokines, J. T., D. P. Zinni, and K. Crowley (2016) Taphonomic patterning of cemetery remains received at the Office of the Chief Medical Examiner, Boston, Massachusetts. *Journal of Forensic Sciences* 61(S1):S71–S81.

Pollock, C. R. (2017) *Organic Staining on Bone from Exposure to Wood and Other Plant Materials*. M.S. Thesis, Boston University School of Medicine, Boston.

Pollock, C. R, J. T. Pokines, and J. Bethard (2018) Organic staining on bone from exposure to wood and other plant materials. *Forensic Science International* 283(1):200–210.

Priess, P. (1973) Wire nails in North America. *Bulletin of the Association for Preservation Technology* 5(4):87–92.

Pye, J. W. (2007) *A Look through the Viewing Glass: Social Status and Grave Analysis in a 19th Century Kansas Cemetery*. M.A. Thesis, University of Arkansas, Little Rock, AR.

Pye, J. W., H. C. Smith, and D. C. Roper (2004) Excavations at the Meadowlark Cemetery, Manhattan. *Current Archaeology in Kansas* 5:77–92.

Pye, J. W., H. C. Smith, and D. C. Roper (2007) With no Stillman among them: Reburial of the Stillman Family Cemetery, Manhattan, Kansas. *Current Archaeology in Kansas* 8:77–92.

Quatrehomme, G., A. Lacoste, P. Bailet, G. Grévin, and A. Ollier (1997) Contribution of microscopic plant anatomy to postmortem bone dating. *Journal of Forensic Sciences* 42(1):140–143.

Robertson, J. I., Jr. (1984) *Tenting Tonight: The Soldier's Life*. Time-Life Books, Alexandria, VA.

Rodriguez, W. C., and W. M. Bass (1985) Decomposition of buried bodies and methods that may aid in their location. *Journal of Forensic Sciences* 30(3):836–852.

Rogers, T. L. (2005) Recognition of cemetery remains in a forensic context. *Journal of Forensic Sciences* 50(1):5–11.

Roksandic, M. (2002) Position of skeletal remains as a key to understanding mortuary behavior. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 95–113. CRC Press, Boca Raton, FL.

Rose, J. C. (ed.) (1985) *Gone to a Better Land: A Biohistory of a Rural Black Cemetery in the Post-Reconstruction South*. Arkansas Archeological Survey Research Series No. 25. Fayetteville, AR.

Rose, J. C., and L. G. Santeford (1985) Burial interpretations. In *Gone to a Better Land: A Biohistory of a Rural Black Cemetery in the Post-Reconstruction South* ed. by J. C. Rose, pp. 130–145. Arkansas Archeological Survey Research Series No. 25. Fayetteville, AR.

Ruck, L., and C. T. Brown (2015) Quantitative analysis of Munsell color data from archeological ceramics. *Journal of Archaeological Science, Reports* 3:549–557.

Rudrappa, T., K. J. Czymmek, P. W. Paré, and H. P. Bais (2008) Root-secreted malic acid recruits beneficial soil bacteria. *Plant Physiology* 148(3):1547–1556.

Ruff, C. B., B. M. Holt, V. Sládek, M. Berner, W. A. Murphy, Jr., D. zur Nedden, H. Seidler, and W. Recheis (2006) Body size, body proportions, and mobility in the Tyrolean Iceman. *Journal of Human Evolution* 51(1):91–101.

Santeford, L. G. (1981) Medicine bottles: One man's (or woman's) cure becomes the archaeologist's tool. In *A Guide for Historical Archaeology in Illinois* ed. by C. E. Orser, Jr., pp. 60–77. Research Paper No. 1, Mid-American Research Center, St. Louis, MO.

Schoenen, D., and H. Schoenen (2013) Adipocere formation—The result of insufficient microbial degradation. *Forensic Science International* 226(1–3):301.e1–301.e6.

Schultz, J. J. (2012) Determining the forensic significance of skeletal remains. In *A Companion to Forensic Anthropology* ed. by D. C. Dirkmaat, pp. 66–84. Wiley-Blackwell, Chichester, UK.

Schultz, J., M. Williamson, S. P. Nawrocki, A. Falsetti, and M. Warren (2003) A taphonomic profile to aid in the recognition of human remains from historic and/or cemetery contexts. *Florida Anthropologist* 56(2):141–147.

Sledzik, P., and M. S. Micozzi (1997) Autopsied, embalmed, and preserved human remains: Distinguishing features in forensic and historic contexts. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 483–495. CRC Press, Boca Raton, FL.

Soil Survey Staff (2014) *Keys to Soil Taxonomy* (12th ed.). National Resources Conservation Service, United States Department of Agriculture, Washington, DC.

Springate, M. E. (2015) *Coffin Hardware in Nineteenth-Century America*. Routledge, London.

Stekel, P. (2010) *Final Flight*. Wilderness Press, Birmingham, AL.

Stødkilde-Jørgensen, H., N. O. Jacobsen, E. Warncke, and J. Heinemeier (2008) The intestines of a more than 2000 years old peat-bog man: Microscopy, magnetic resonance imaging and 14C-dating. *Journal of Archaeological Science* 35(3):530–534.

Stojanowski, C. M., R. M. Seidemann, and G. H. Doran (2002) Differential skeletal preservation at Windover Pond: Causes and consequences. *American Journal of Physical Anthropology* 119(1):15–26.

Takatori, T. (2001) The mechanism of human adipocere formation. *Legal Medicine* 3(4):193–204.

Taylor, A. J., A. A. Fox, and I. W. Cox (1986) *Archaeological Investigations at Morgan Chapel Cemetery (41BP200), a Historic Cemetery in Bastrop County, Texas*. Archaeological Survey Report No. 146, Center for Archaeological Research, University of Texas, San Antonio, TX.

Tebb, W., and E. P. Vollum (1905) *Premature Burial and How It May Be Prevented, with Special Reference to Trance, Catalepsy, and Other Forms of Suspended Animation* (2nd ed.) Swan Sonnenschein, London.

Trinkley, M., and D. Hacker-Norton (1984) *Analysis of Coffin Hardware from 38CH778, Charleston County, South Carolina*. Research Series 3, Chicora Foundation, Inc., Columbia, SC.

Ubelaker, D. H. (1995) Historic cemetery analysis: Practical considerations. In *Bodies of Evidence: Reconstructing History through Skeletal Analysis* ed. by A. Grauer, pp. 37–48. Wiley-Liss, New York.

Ubelaker, D. H., and N. D. Sperber (1988) Alterations in human bones and teeth as a result of restricted sun exposure and contact with corrosive agents. *Journal of Forensic Sciences* 33(2):540–548.

Ubelaker, D. H., and K. M. Zarenko (2011) Adipocere: What is known after over two centuries of research. *Forensic Science International* 208(1–3):167–172.

Vanzetti, A., M. Vidale, M. Gallinaro, D. W. Frayer, and L. Bondioli (2010) The iceman as a burial. *Antiquity* 84(325):681–692.

Villa, P. (1982) Conjoinable pieces and site formation processes. *American Antiquity* 47(2):276–290.

Walker, T. S., H. P. Bais, E. Grotewold, and J. M. Vivanco (2003) Root exudation and rhizosphere biology. *Plant Physiology* 132(1):44–51.

White, E. M., and L. A. Hannus (1983) Chemical weathering of bone in archaeological soils. *American Antiquity* 48(2):316–322.

Wilkinson, D. M., H. J. O'Regan, and T. Clare (2006) Where are the non-human bog bodies? *Journal of Wetland Archaeology* 6(1):99–104.

Willey, P., and A. Heilman (1987) Estimating time since death using plant roots and stems. *Journal of Forensic Sciences* 32(5):1264–1270.

Wilson, A. S., R. C. Janaway, A. D. Holland, H. I. Dodson, E. Baran, A. M. Pollard, and D. J. Tobin (2007) Modelling the buried human body environment in upland climes using three contrasting sites. *Forensic Science International* 169(1):6–18.

Yalom, M. (2008) *The American Resting Place*. Houghton Mifflin, Boston.

Zelinka, S. L., and D. S. Stone (2011) The effect of tannins and pH on the corrosion of steel in wood extracts. *Materials and Corrosion* 62(8):739–744.

Fluvial Taphonomy

6

THOMAS EVANS

Contents

> It is the task of the natural scientist to search for laws which will enable him to deduce predictions. This task may be divided into two parts. On the one hand, he must try to discover such laws as will enable him to deduce single predictions ("causal" or "deterministic" laws or "precision statements"). On the other hand, he must try to advance hypotheses about frequencies, that is, laws asserting probabilities, in order to deduce frequency predictions.
>
> **—Karl Popper**
> *The Logic of Scientific Discovery* (1959)

Introduction

Human remains routinely enter fluvial systems through natural (i.e., erosion of cemeteries and archaeological sites), accidental (i.e., drowning), suicidal, and criminal (i.e., body disposal or intentional drowning) events (see Chapter 7, this volume). Regardless of the mechanisms of entry into a river, accidental or intentional, it is beneficial for human material to be recovered and subjected to a forensic or anthropological analysis. If the remains are the product of criminal activity, discovery of additional remains may be beneficial for the prosecution by increasing the potential for identification, cause, and manner of death determination (Komar and Potter 2007) and/or aiding in the location of a crime scene. Unfortunately, searching for any materials (i.e., evidence, remains, etc.) in rivers is difficult, slow, and complicated (see also Becker 2000; Dutelle 2007; Glassey

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2014; McUne and Gagnon 2007; Tackett and Whitfield 1987; Teather 1994), especially due to the significant physical hazards for diving personnel (Burke and O'Rear 1998; Falkenthal 1999). A greater understanding of fluvial transport and deposition of remains increases the recovery potential of evidence and remains by narrowing search areas. In addition, the forensic anthropologist can use diagnostic tools to aid in identifying potential taphonomic histories of the remains that they analyze. Such tools include an understanding of fluvial taphonomic processes and the associated taphonomic modifications due to these processes.

The purpose of this chapter is to inform the reader of our present understanding of fluvial taphonomic processes and to describe the resulting taphonomic modifications (i.e., the results of the processes). What follows covers decay in rivers, full body transport, articulated body part transport, isolated bone transport, and the analytical techniques that can be used to interpret skeletal remains recovered from a fluvial context. Each section includes a description of the taphonomic modifications that can aid investigators in diagnosing a fluvial history for remains when this information is available.

Since there is a paucity of literature covering human fluvial taphonomy, literature from other fields (e.g., zoology and paleontology) has been incorporated; however, the reviewed literature has been restricted to observational and experimental research. Some review articles concerning fluvial taphonomic processes are not included here, but the interested reader should seek these resources directly (Haglund and Sorg 2002; Osterkamp 2011; Rodriguez 1997). In addition, no information about sediment transport theory is presented regarding isolated bone transport; a review of this literature is beyond the scope of this chapter, and the interested reader should access any of the many textbooks (Thorne et al. 1987) and reviews (Middleton and Southard 1984; Parker 2006) on the subject.

Previous Research

Historically, research concerning the transport of remains in rivers has been performed in the fields of paleontology and archaeology, and both fields face similar analytical problems to the forensic scientist: the reconstruction of the past from fragmentary or partial evidence. Since the evidence interpreted by paleontology and archaeology is nearly entirely skeletal, most research has focused on the transport and deposition of isolated bones, with few exceptions. Similarly, most literature reviews focus on isolated bones, for example, in paleontology (Behrensmeyer 1990, 1991; Rogers and Kidwell 2007; Shipman 1981), archaeology (Boaz 1982; Gifford 1981; Lyman 1994), and most recently in forensics (Evans 2006, 2015; Haglund and Sorg 2002; Nawrocki et al. 1997).

Given the interest in fluvial taphonomy in three disciplines (paleontology, archaeology, and forensics), what is the state of our understanding of fluvial processes and taphonomic signatures? Surprisingly, we know very little, since most research has used small sample sizes, poor or no controls, unknown or unreported sample histories, and poorly reported experimental conditions, resulting in most data and interpretations yielding preliminary or tentative results. Presently, it is not possible to combine all studies into a coherent corpus of understanding; there are conflicting observations and conclusions, which raise doubts and concerns related to the applicability of many of the conclusions presently in the literature. There is also a considerable amount of speculation in the literature about how fluvial processes take place, most of which have no basis in published observations or experimentation. Presented here is a comprehensive and straightforward analysis of the published literature to determine what we understand and what is still opaque.

Decay in Fluvial Systems

Tissue decay in rivers proceeds differently than decay in lakes and ponds, since the decay products are swept downstream, the biota is different in flowing water, currents physically buffet tissues (Piorkowski 1995), bodies fall apart as they impact the bed during transport (Kline et al. 1997; Piorkowski 1995), and the effects of temperature and seasonality manifest differently in rivers. Consequently, this review will not include the decay of bodies in lakes, ponds, wells, tubs, or any other standing body of water.

Decay of tissues in rivers is integral to the taphonomic history of fluvially altered remains, since decay produces the different entities that are transported and deposited in rivers. Intact bodies move and are altered differently than articulated units and isolated bones. As such, it is important to consider what units are produced during decay and how these units will be altered differently as they move in different ways downstream. Unfortunately, the disarticulation sequence of human bodies in rivers is still poorly understood, which complicates our understanding of which articulated units are transported and the approximate order in which isolated bones become available for transport.

Little information is available on how tissue breakdown occurs in fluvial environments or the rate at which it occurs (but see Chaloner et al. 2002; Piorkowski 1995; Rayo et al. 2014), as well as how the processes might change depending on the season. What can be stated with confidence is that decay is slower in fluvial systems than on land (Hobischak 1997a,b; Hobischak and Anderson 2002; MacDonell and Anderson 1997), most likely due to lower temperatures (Byard 2018; Doberentz and Madea 2010; Heaton et al. 2010; Madea 2002; Petric et al. 2004; Reh 1969; Reh et al. 1977) and lack of terrestrial vertebrates and invertebrate scavengers (Chapters 3 and 9). Terrestrial invertebrates will colonize body parts that are exposed above the water surface, thus hastening decay (Barrios and Wolff 2011; Haglund 1993; Hobischak 1997a,b; Hobischak and Anderson 2002; Kline et al. 1997; MacDonell and Anderson 1997; Mann et al. 1990:109; Parmenter and Lamarra 1991; Piorkowski 1995; Rayo et al. 2014), while partial submersion in water can keep tissues wet enough for terrestrial invertebrate colonization in environments where desiccation would occur otherwise (Goff and Odom 1987:47–48). In the absence of insect consumption, soft tissue above water can become mummified, even while the rest of the body is submerged. The amount of flesh above and below water changes as bodies sink and float throughout decay (Hobischak 1997a,b; Hobischak and Anderson 2002; MacDonell and Anderson 1997). In addition, it appears that decay is faster in flowing water than in stagnant water (Palmer 2020).

Like terrestrial decay, the warmer the water, the faster the decay (Minshall et al. 1991; Palazzo et al. 2020; Palmer 2020). Once in water, a body is rapidly colonized by invertebrates (Brusven and Scoggan 1969; Cleason et al. 2006; Duband et al. 2011; Kline et al. 1997; MacDonell and Anderson 1997; Parmenter and Lamarra 1991; Piorkowski 1995; Vanin and Zancaner 2011), which facilitate tissue breakdown, including crustaceans of all sizes (Duband et al. 2011; Mottonen and Nuutila 1977:1097–1098; Pascali et al. 2020; Petric et al. 2004; Rayo et al. 2014; Vanin and Zancaner 2011; Wallace 2019). Invertebrates can be found all over a submerged body (Chaloner et al. 2002; Duband et al. 2011; Minakawa 1997; Piorkowski 1995), although they are most often located near body orifices and locations of trauma (Brusven and Scoggan 1969; Cleason et al. 2006; Chaloner et al. 2002; Haglund 1993; Heaton et al. 2010; Kline et al. 1997; Medina et al. 2015; Minakawa 1997; Piorkowski 1995; Rayo et al. 2014; Schuldt and Hershey 1995; Vanin and Zancaner 2011) or on the sheltered underside of bodies in fast flows (Kline et al. 1997; Piorkowski 1995). Aquatic invertebrates can be used as a postmortem submergence interval (PMSI) indicator (Barrios and Wolff 2011; Medina et al. 2015; Wallace et al. 2007, 2008), although in some places and habitats, there is no consistent succession of invertebrates on decaying bodies (Keiper et al. 1997; Hobischak 1997a,b; Piorkowski 1995). Unfortunately, the invertebrates present in a river change depending on the season (Hobischak 1997a,b; Hobischak and Anderson 2002) as well as the microhabitat (riffle vs. pool) (Brusven and Scoggan 1969; Chaloner et al. 2002; Hobischak 1997a,b; Hobischak and Anderson 2002; Keiper et al. 1997; MacDonell and Anderson 1997), which complicates the use of invertebrates as a PMSI indicator. Mold or algae are often intimately involved in aqueous decomposition (Casamatta and Verb 2000; Chaloner et al. 2002; Cleason et al. 2006; Haefner et al. 2004; Hobischak and Anderson 2002; Keiper et al. 1997; Kline et al. 1997; Minshall et al. 1991; Parmenter and Lamarra 1991; Piorkowski 1995; Rayo et al. 2014), with aquatic organisms growing faster in warmer water, thus facilitating faster decay (Minshall et al. 1991). Microbial life can also control decay in fluvial systems (Hobischak and Anderson 2002; Kline et al. 1997; Piorkowski 1995), although this mechanism of decay has rarely been reported.

Little has been written concerning fish scavenging on human remains in fluvial systems, with our data set relying heavily on case reports (Simões 2018; Valente-Aguiar et al. 2020). Fish modification to remains ranges from nearly complete consumption of soft tissues to minor lesions (Simões 2018; Valente-Aguiar et al. 2020). What defects are produced are species-specific, with some fish consuming remains from the inside out (Valente-Aguiar et al. 2020), while others scavenge preferentially on exposed tissues, though they can be found under clothing at autopsy (Simões 2018; Valente-Aguiar et al. 2020). Further research regarding fish scavenging is needed to characterize how fish interact with remains and the modifications that they produce, and catalog the damage caused by different species of fish.

Bodies from rivers tend to have a consistent sequence of decay prior to disarticulation (Doberentz and Madea 2010; Heaton et al. 2010; Hobischak 1997a,b; Hobischak and Anderson 1999, 2002; MacDonell and Anderson 1997; Madea 2002; Madea and Doberentz 2010; Palmer 2020; Perry 2005; Petric et al. 2004; Rayo et al. 2014; Reh 1967, 1969; Reh et al. 1977; Seet 2005), beginning with the development of "washer woman's skin," skin discoloration (e.g., marbling and black discoloration), distension and bloating, skin peeling, hair loss, loss of nails, and loss of skin. Finally, progressive skeletonization and disarticulation occur, proceeding generally from distal to proximal joints (Haglund 1993), although there is variability in the observed disarticulation sequence.

Presently, there are three common fluviatile PMI/PMSI indicators: invertebrate succession, algal succession, and the sequence of body decay. If local invertebrate and algal information is unavailable, then using the decomposition research of Doberentz and Madea (2010), Heaton et al. (2010), Hobischak (1997a,b), Hobischak and Anderson (1999, 2002), Madea (2002), MacDonell and Anderson (1997), Madea and Doberentz (2010), Palazzo et al. (2020), Palmer 2020; Rayo et al. (2014), Reh (1967, 1969), Reh et al. (1977), Reijnen et al. (2018), and Seet (2005) to estimate PMI/PMSI is presently the best practice (see also van Daalen et al. 2017; De Donno et al. 2014). There are several reviews and articles regarding the use of aquatic insects (Barrios and Wolff 2011; Haskell et al. 1989; Hawley et al. 1989; Hobischak and Anderson 2002; Keiper et al. 1997; Keiper and Casamatta 2001; Medina et al. 2015; Merritt and Wallace 2001) and algae (Casamatta and Verb 2000; Haefner et al. 2002, 2004; Keiper and Casamatta

2001) to determine PMI/PMSI. Recently, a new method of PMI/PMSI determination has been proposed by measuring the microbial succession on remains (Benbow et al. 2015; Lang et al. 2016). While this technique has promise, it is unclear if regional or watershed-specific baseline data are needed before the technique will be practically useful for casework.

Full Body Transport

Little has been published concerning the transport of full bodies in fluvial environments; consequently, our understanding is extremely limited. Nearly all data on the subject come from anecdotes (Darwin 1839:141), case reports (D'Alonzo et al. 2012; Kakizaki et al. 2010; Mann et al. 1990:109; Peyron et al. 2018), or disasters (Berryman et al. 1988:844; Moore et al. 2008; Moore and Varricchio 2018; Varricchio et al. 2005). Human bodies have a density near that of water (Donoghue and Minnigerode 1977). Consequently, bodies can be expected to float and sink repeatedly depending on several variables including state of decay and density of water (salt and sediment concentrations) (Heaton et al. 2010). Warmer water leads to faster bloating, so remains will float earlier during the PMSI, consequently moving downstream sooner. The bulk density of the body determines floatation, which includes any clothing or objects attached to a body. Body floatation is common and increases the rate of transport considerably, since the body is moving slightly slower than the fluid medium. Often, transport is episodic (Moore and Varricchio 2018; Strobel et al. 2009), though typically faster and more common during periods of higher water (Bickart 1984:527–528; D'Alonzo et al. 2012; Glock et al. 1980; Guatame-Garcia et al. 2008; Moore and Varricchio 2018; *contra* Strobel et al. 2009). Intermittent transport is caused by a body being caught on the upstream side of woody debris, rocks, or other channel obstructions (Cederholm and Peterson 1985; Cederholm et al. 1989; 1999:9–10; Heaton et al. 2010; Hobischak and Anderson 1999; Minakawa 1997; Minakawa and Gara 2005; Moore and Varricchio 2018; Peyron et al. 2018; Piorkowski 1995; Rodriguez 1997:461; Strobel et al. 2009; Teather 1994:6–8, 10, 29–30). In addition, pools or eddies behind obstructions (woody debris or rocks) can also trap bodies and stop downstream transport (Brooks and Brooks 1984, 1997; Cederholm et al. 1989; Minakawa 1997; Minakawa and Gara 2005; Piorkowski 1995; Strobel et al. 2009). Sediment bars of any kind also can be loci of body deposition (Butler 1987:133; Glock et al. 1980; Haglund et al. 1990; Moore and Varricchio 2018); however, channel obstructions and eddies/pools retain most bodies (Cederholm et al. 1989; Cederholm and Peterson 1985; Minakawa 1997; Minakawa and Gara 2005; Strobel et al. 2009). Therefore, more episodic and lower net transport is expected in rivers with more obstructions, and faster and more continuous transport is expected in rivers with no or fewer obstructions. Bodies can be transported hundreds of miles in days or months in large river systems (Bassett and Manhein 2002; Blanco Pampín and López-Abajo Rodríguez 2001; Brady 2012; D'Alonzo et al. 2012); therefore, the longer a body is missing, the farther downstream it may have traveled. This is not always the case, as bodies have been found upstream of their river entry location (Bassett and Manhein 2002; Brewer 2005; Heaton et al. 2010). In larger rivers, bodies tend to stay on the same side of the river that they entered (Bassett and Manhein 2002; Brewer 2005; Dilen 1984).

It should be noted that none of the previous research concerning fluvial transport of full bodies includes a taphonomic description of the human bodies recovered. Consequently, any taphonomic interpretations of the history of a body recovered from a river should be governed by the context of recovery as well as indicators of decay taking place under water.

Articulated Unit Transport

Like full body transport, articulated unit transport has received little attention in the experimental or observational literature, and what has been published has entirely utilized faunal (nonhuman) remains. This is a function of the difficulty in obtaining human remains for destructive experimentation as well as difficulty in obtaining permits to run experiments in public waterways using human remains. It is useful to note that the disarticulation sequence of human body parts in rivers is nearly unknown and consequently so are the articulated parts typically transported in fluvial systems resulting from this disarticulation. In addition, the amount of soft tissue that was present on articulated parts during fluvial transport and prior to the recovery of skeletonized remains is also unknown, so no modeling or hypothesis formation can take place without further observations and experiments into fluvial decay processes.

Like full bodies, articulated elements move most often and furthest during higher flow events (Bickart 1984; Gifford 1977:166, 187; Gifford and Behrensmeyer 1977:250). It is unclear if articulated units have a greater transport potential, since articulation, in comparative studies with isolated bones, yielded both faster (Coard 1999; Coard and Dennell 1995; Trapani 1996, 1998) and slower (Coard and Dennell 1995) transport. More authors have observed an increased dispersal potential, so *in toto*, it appears that articulation generally increases transportability with some exceptions. As more skeletal elements are articulated, preferred orientations of bones become more cryptic, with bone orientations no longer reflecting flow direction. Articulated units often adopt long-axis orientations that are either parallel or perpendicular to the flow direction (Coard 1999; Coard and Dennell 1995). Temporary burial (complete or partial) slows net transport considerably. The shape of articulated elements contributes to transport potential (Trapani 1996, 1998), but the way shape alters transport is not well understood. Dry articulated units tend to move faster than saturated parts (Coard 1999), particularly when they float. Floating can also occur from decay gases building up in tissues, causing the entire unit to float (pers. obs.). Floatation increases the transport potential of articulated units dramatically (Coard 1999). It also provides a transport mechanism that does not leave any observable trace on the soft or osseous tissues.

Little research has described the taphonomic modifications caused by the transport of articulated material. Consequently, taphonomic history interpretations of articulated remains found in rivers should be governed primarily by the context of recovery. Since articulated remains are often partially devoid of flesh, some of the taphonomic modifications isolated bones' experience from fluvial transport, may also apply to articulated remains.

Isolated Bone Transport

Introduction

Fluvial systems are immensely complicated, making the transport of any material in a river difficult to describe, let alone fully understand. Presented here is a synopsis of what we understand about isolated bone transport, starting with bone floatation and saturation with water, the factors that alter bone transport rates, a discussion of what taphonomic modifications may be found on remains, an evaluation of analytical techniques for remains recovered from fluvial environments, and a brief discussion of sheet flow (a way in which bones enter fluvial systems).

Bone Floatation and Saturation

Bone floatation has been observed by many investigators in laboratory and field experiments as well as during aqueous decay experiments (Table 6.1). Similarly, bone floatation has been observed in bones of all sizes (rodent up to elephant) and from many taxa (amphibians, birds, and mammals) (Table 6.1). Consequently, this mode of transportation should not be ignored, since it is common and can cause rapid downstream movement without producing evidence to suggest that the process occurred. Bone floatation occurs when the bulk density of a bone (Chapter 4) is less than the fluid medium in which it resides. These conditions can occur after dry periods with lower flow, followed by rapid river rise, potentially entraining dry skeletal material in higher flows. In addition, fresh skeletal material may float, caused by the buildup of decay gases inside the bone (Ayers 2010; pers. obs.).

Behrensmeyer (1973:31–32) measured mammal bone bulk densities, which ranged from 0.64 to 2.30 g/cm^3 (Appendix 2, pp. 174–175). Gutierrez and Kaufmann (2007) reported bulk densities for juvenile guanaco (*Lama guanicoe*) bones that ranged from 0.63 to 2.12 g/cm^3 (2007:156, Table 6.1) and 0.55 to 2.42 g/cm^3 (2007:157, Table 6.2) for adult bones. Kaufmann et al. (2011:341, Figures 6.3 and 6.4) depicted the range of densities for wet and dry guanaco bones and demonstrated that both wet and dry bones can have densities below 1.0 g/cm^3. Yang et al. (2011: Figures 6.1 and 6.2 and Table 6.1) reported the dry density of Dybowski's frog (*Rana dybowskii*) femora as between ~0.55 and just slightly higher than ~1.00 g/cm^3, with the density increasing slightly with age. These observations of initial bone densities suggest that many bones will at first float in water. Similarly, Young (1989:12, 49) reported densities of subfossil (partially mineralized) bone ranging from 1.40 to 3.06 g/cm^3 and modern bones ranging from 1.00 to 2.10 g/cm^3. His observations suggest that skeletal material on river beds can have densities close to 1.00 g/cm^3 even when (partially) saturated with water, making bones easy to transport or float.

When placed in water, bones begin to hydrate, increasing their bulk density. The rate at which bones hydrate is variable, with some bones becoming saturated in a matter of hours, while others can take months (Table 6.2). Since bone density is continually changing during hydration, it is difficult to determine the transport properties of bones that have recently entered a river and are yet to undergo full saturation. During hydration, bones will move faster and more readily than when saturated, since they have a lower density and require less force to initiate and maintain transport. The analyst should be aware that bones that have been in river systems for days, weeks, and even months still may not be saturated and may be capable of partial or complete floatation, facilitating their faster and more frequent transport.

Bone floatation is undetectable, since floatation itself produces no permanent taphonomic modifications on osseous remains, so it is best to consider floatation as a possibility when interpreting any skeletal assemblage recovered from a fluvial environment.

Factors That Alter Bone Transport Rates

During fluvial transport, bones move faster than other clastic material (Pavlish et al. 1998, 2002; Schick 1984, 1986, 1987), and which bones have a higher transport potential depends on a number of factors, including taxon, size (Blob 1997; Pante and Blumenschine 2009, 2010; Pavlish et al. 2002), mass (Domínguez-Rodrigo et al. 2018; Knell 2009; Kontrovitz and Slack 1991; Morden 1991a,b), density (dry or wet) (Boaz and Behrensmeyer 1976; Coard 1999; Evans 2015), shape (Blob 1997; Domínguez-Rodrigo et al. 2018; Evans 2015;

Table 6.1 Studies of Floating Bones, Including Bones Observed, Taxa, Duration, and the Type of Aqueous Environment in Which the Bones Were Floating

Reference	Floating Bones	Taxa	Duration of Floatation	Aqueous Environment
Alley 2007:39, 40, 42	Ribs, thoracic vertebrae, and articulated vertebrae	Pig (*Sus scrofa*)	1-2 weeks	Standing Water
Ayers 2010:37, Table 6.3; 27, Table 6.5; 35, Appendix C; 82, 83, 92	Vertebrae, phalanges, other bones	Pig (*Sus scrofa*)	1-2 days	Standing Water
Behrensmeyer 1973:31	Foot bones and vertebrae	Not reported	Hours	Standing Water
Behrensmeyer 1975:485	Foot bones and vertebrae	Not reported	Hours	Standing Water
Boaz and Behrensmeyer 1976:57, Figure 6.2	Cranium	Human (*Homo sapiens*)	Not reported	Flume
Coard 1999:1371	Thoracic and lumbar vertebrae, ribs, and sacrum	Mouflon sheep (*Ovis musimon*), Pig-tailed macaque (*Macaca nemestrina*), Alsatian dog (*Canis familiaris*)	7–30 meters	Flume
Coard and Dennell 1995:447	Cranium	Pig-tailed macaque (*Macaca nemestrina*)	Not reported	Flume
Dodson 1973:18	Nearly every bone in the body	Mouse (*Mus*) and frog (*Rana*)	Few days (mouse), month (frog)	Standing Water
Evans 2010:28	Not reported	Not reported	Month and a half	River, standing water
Frison and Todd 1986:67	Smaller elements	Indian elephant (*Elephas maximus*)	Minutes	River
Gnidovec 1978:18; 19, Figure 6.8; 20, Table 6.3; 21	Not reported	Mammals, birds, and herpetofauna	3 hours	Standing Water
Gutierrez and Kaufmann 2007: 155, Figure 6.2; 158	Lateral tuberosity, head, distal epiphysis of humerus, femur, caudal vertebrae, sacral vertebrae, and others	Guanaco (*Lama guanicoe)*	Several hours	Standing Water
Kaufmann et al. 2011	Many, see Tables 6.1–6.3	Guanaco (*Lama guanicoe)*	Minutes	Flume
Morden 1991a:77	Cervical vertebra, thoracic vertebra, ribs, calcaneus, and metacarpal	Human (*Homo sapiens sapiens*)	5 days	Standing Water
Trapani 1996:116, 148	Cranium, most bird bones	Pigeon (*Columbia livia*)	Not reported	Flume
Trapani 1998:480, Table 6.1; 481	Cranium	Pigeon (*Columbia livia*)	Not reported	Flume
Voorhies 1969:67, text and footnote	Sacrum and sternum	Sheep, coyote (species not reported)	Not reported	Flume
Personal Observations	Nearly every skeletal element	Mammals, birds, frogs, salamanders, snakes, lizards	Seconds to 2.5 months	Buckets, rivers, settling columns, etc.

Table 6.2 Observations of the Time to Saturation or Time to Sinking

Reference	Time to Saturation or Sinking
Behrensmeyer 1973:31–32, Figure 6.2	Hours, 70+ hours (time to saturation)
Behrensmeyer 1975:485, Figure 6.2; 486	Hours, 70+ hours (time to saturation)
Coard and Dennell 1995:442	5–7 days (time to saturation)
Dodson 1973:18	Few days to a month (time to sinking)
Gnidovec 1978:18; 19, Figure 6.8; 20, Table 6.3; 21	8– 83 hours (time to sinking)
Gutierrez and Kaufmann 2007:155, Figure 6.2; 158	Hours (time to saturation)
Trapani 1996:82–83, Table 6.1; 84	2–13 days (time to saturation)
Young 1989:12, 49	Bones released gas for over half an hour
Personal Observation	2.5 months (time to sinking)

Morden 1991a,b), projected surface area (Coard 1999; Kontrovitz and Slack 1991), orientation (Blob 1997; Elder 1985), age of organism (Kaufmann et al. 2011), weathering stage, and freshness (presence of grease) (Morden 1991a,b). Recent empirical and observational research has determined that bulk density controls bone transport when bone density is less than the surrounding water (e.g., when bones float), and interactions with the river bed control transportability when bones have a greater density than the surrounding medium (Evans 2015). To understand this nuanced understanding of bone transport, it is useful to comprehend previous research on the subject.

Previous research has indicated that larger bones (length, volume, area, or diameter) tend to move slower than smaller bones (Brady 2005; Brady and Rogers 2005, 2007; *contra* Boaz and Behrensmeyer 1976), with the converse also being true; smaller bones under some conditions move farther, faster, and more readily than larger bones (Aslan and Behrensmeyer 1996; Duckworth 1904; Evans 2007; Long and Langer 1995:88; Nawrocki and Pless 1993; *contra* Andrews and Whybrow 2005). As expected, some larger bones are left behind when transport occurs to other elements (Long and Langer 1995:88; Spennemann 1992; Weigelt 1989 [1927]:36). It should be noted that there is a good deal of variation in transport potentials, so smaller bones can move less than larger bones, and vice versa (Aslan and Behrensmeyer 1996; Hanson 1980; pers. obs.). Similarly, it has been observed that light bones move farther, more readily, and more rapidly (Domínguez-Rodrigo et al. 2018; Duckworth 1904; Evans 2007; Long and Langer 1995:88; Nawrocki and Pless 1993; *contra* Andrews and Whybrow 2005) than larger and heavier bones (Aslan and Behrensmeyer 1996), with denser bones tending to move slower than less dense bones as suggested by faster bone movement when bones are dry and slower movement when wet (Coard 1999; Evans 2010; Kaufmann et al. 2011; Morden 1991a). Similarly, fresh (unweathered) bones tend to move faster in a flow than degreased or weathered bones (Morden 1991a), which may be a function of bone density changes caused by degreasing.

Both shape and orientation have been suggested as dramatically altering bone transport, with both variables functioning in concert. Previous authors have suggested that shape governs the transport characteristics of some bones (innominates, scapulae, vertebrae, etc.), and bone transport properties change when they break (Boaz and Behrensmeyer 1976; Corbat et al. 2017) or are abraded. Authors observed that during transport or exposure to a current, skeletal material often adopts a stable orientation that yields less net transport (Frison and Todd 1986:61–69). Flat bones tending to lay flat on the river bed and not move (Boaz and Behrensmeyer 1976; Elder 1985; Evans 2007; Gifford 1977:165, 187–198; Gifford and Behrensmeyer 1977:261–263), while skeletal elements with processes or other portions that extend upward from the river bed and higher into the flow tend to have higher transport potentials (Coard and Dennell 1995). Concavo-convex elements have been observed orienting convex-up most frequently (Dodson 1973; Elder 1985; Evans 2007; Gifford 1977; Gifford and Behrensmeyer 1977; Knell 2009; Trapani 1996; Voorhies 1969), and move slowly, if at all. Experimental research often showed elongate bones tend to orient parallel or perpendicular to flow with parallel orientation most common when water depths greatly exceed the height of a bone (Boaz and Behrensmeyer 1976; Coard and Dennell 1995; Dodson 1973; Domínguez-Rodrigo et al. 2018; Elder 1985; Morden 1991a; Pavlish et al. 2002; Voorhies 1969) and perpendicular orientation predominates with shallower flow (Voorhies 1969) or when bones orient parallel to the lee side of bedforms (Pavlish et al. 2002; Trapani 1996, 1998; Voorhies 1969). When long bones orient parallel to flow, the heaviest end tends to be downstream (Boaz and Behrensmeyer 1976; Voorhies 1969). Similarly, open diaphysis tubes (cylinders) orient parallel to flow and are filled or covered by sediment rapidly and do not move (Evans 2007; Morden 1991a).

These results can be confusing to interpret, because many results seem mutually contradictory. This is largely a function of research methods and study designs. Most reviewed research involved small sample sizes and took place for short durations (hours or days) or in flumes (artificial rivers in a laboratory). Such studies reduce the complexity of real fluvial systems, thus removing the reality of bones changing over time as well as river variability. In longitudinal empirical trials involving thousands of bones over years in a variety of rivers, Evans (2015) observed that there were two variables that governed bone transport. First, bone density explained most transport of low-density clasts, those bones that floated. Secondly, for those bones that were denser than water, their transport was better understood by the bone's interactions with the riverbed. In other words, when bones are low density, they float and move quickly, and when they are higher density their interactions with the bed dictate how fast they move. It appears that, for dense bones, interactions with the bed ultimately govern bone transport, since stabilization of bones in/on the bed prevents their movement temporarily or permanently (Frison and Todd 1986:61–69; Yezzi-Woodley et al. 2018). Bedforms alter all aspects of bone transport, including the rate (velocity), orientation, and mode of movement (Trapani 1996, 1998). Bedform migration over bones temporarily stops their movement (Evans 2015; Pavlish et al. 2002; Trapani 1996, 1998; Voorhies 1969), although the magnitude of this effect depends on bone length. If long bones are parallel to flow and are covered by a bedform with a shorter wavelength than the length of the bone, then those bones are never fully exposed before the next bedform migrates over them, keeping the bone permanently buried (Trapani 1996, 1998). Besides burial, scour around a bone can stabilize its location or orientation, thus reducing bone transportability (Frison and Todd 1986:61–69; Hanson 1980). Similarly, bones can trap other skeletal material by pinning them down (Evans 2015; Pavlish et al. 2002) or creating eddies in which other bones are deposited (Brady 2005; Pavlish et al. 2002), thus stabilizing bone locations. Generally, bones move toward areas in a flow with lower flow velocities including moving upstream into the troughs of bedforms (Evans 2015; Trapani 1996, 1998).

Fluvially Derived Taphonomic Modifications

Abrasion can take many forms on a bone surface including bone smoothing, rounding, polish (sometimes shiny), scratches, gouges, frosting, pitting, denting, chipping, grooves, cracking, and notches. Rarely are long grooves and scratches produced (Shipman and Rose 1983:77–80; Shipman and Rose 1988). In addition to these individual marks, the bone surface will generally become thinner, eventually leading to small openings (*windows*) that enlarge with further abrasion (DeBattista et al. 2013; Fernández-Jalvo and Andrews 2003; Griffith et al. 2016; Korth 1978, 1979; Nawrocki et al. 1997; Chapter 7). Similarly, lacunae and vascular canals (any natural opening) will gradually enlarge (Bromage 1984; Nawrocki et al. 1997; Thompson et al. 2011:791, Figure 3.4). Articular surfaces rapidly thin to expose underlying cancellous bone (Fernández-Jalvo and Andrews 2003; Korth 1978, 1979; Llona and Andrews 1999), and in juvenile vertebrates, the epiphyses will detach if not fused (Fernández-Jalvo and Andrews 2003). Edges can be fractured or chipped as well (Andrews 1990).

River seeding experiments indicate that the abrasion state of skeletal material does not correlate with transport distance (Aslan and Behrensmeyer 1996:414; Van Orden and Behrensmeyer 2010). For example, lighter bones can be moved faster and further with little abrasion, while larger bones could move less and be "sandblasted" in place (Thompson et al. 2011; Van Orden and Behrensmeyer 2010). Bones have moved hundreds of meters or kilometers downstream without showing signs of abrasion (Behrensmeyer et al. 1989:116; Hanson 1980; pers. obs.), while abrasion in the form of scratches, scrapes, pitting, and gouging has been observed on bones with as little as 1 km of fluvial transport (Herrmann et al. 2004). Consequently, no correlation exists between transport distance and abrasion state, so abrasion should not be used as a transport distance estimation tool or as a fluvial PMSI indicator. There is no clear picture of how much abrasion is caused by transport and with what sediment types (but see Thompson et al. 2011), although it seems that larger clasts (or higher energy) are needed to cause extensive rounding on a bone (Evans 2007). Since many bones with a known transport history show no or minimal abrasion, the presence of abrasion on bones suggests an episode of prior fluvial transport, but the opposite cannot be taken as indicative of a lack of fluvial transport.

Acid etching of bone surfaces usually occurs over nearly the entire bone surface and presents as a delocalized surface roughening (Duckworth 1904). Small pits form, expand outward, and finally connect, making irregular and rough galleries in the bone surface. Often, acid etching is accompanied by bone discoloration (Amadasi et al. 2015), possibly caused by the same acids that are etching the bone. Determining when acid etching will occur is primarily a function of the ions present in the solution surrounding a bone and their concentration. For freshwater with few ions in solution, any acid in solution should start to degrade bone. Christensen and Myers (2011) observed bovine bone degradation under different pHs and found that a pH of 7 did very little damage to the bone, while low pHs (4 and 1) were associated with significant bone degradation. Similar results were observed for cooked salmon bones degraded in different pH solutions by Collins (2010). Harnett et al. (2011) observed the progressive dissolution of bone in HCl and H_2SO_4 and graphed mass loss over time. They noted that bone surfaces became porotic and pitted prior to complete dissolution. Amadasi et al. (2015) observed bone damage caused by different pHs and observed more bone damage due to alkaline conditions than acidic conditions. They also noted an increase in microscopic cracking around osteons when submerged in solutions with more cracking found in the most alkaline conditions. None of these studies are directly analogous to fluvial systems, however, because bones reacted in standing bodies of water keep the reaction products in solution with the bone and thus establish a dynamic equilibrium over time. Fluvial systems have continuous water flow, and reaction products cannot build up around a bone, so more acid etching is expected in even mildly acidic rivers than was observed in the work of Amadasi et al. (2015), Christensen and Myers (2011), Collins (2010), or Harnett et al. (2011). Figures 6.1 and 6.2b display bones recovered from an acidic river showing mild to advanced acid etching.

Discoloration of bones can occur from a variety of agents, most of which are poorly understood or unknown (Chapters 11 and 12). The most common color change is to a light or medium brown (see Figure 6.2), which appears to be caused by partial or complete

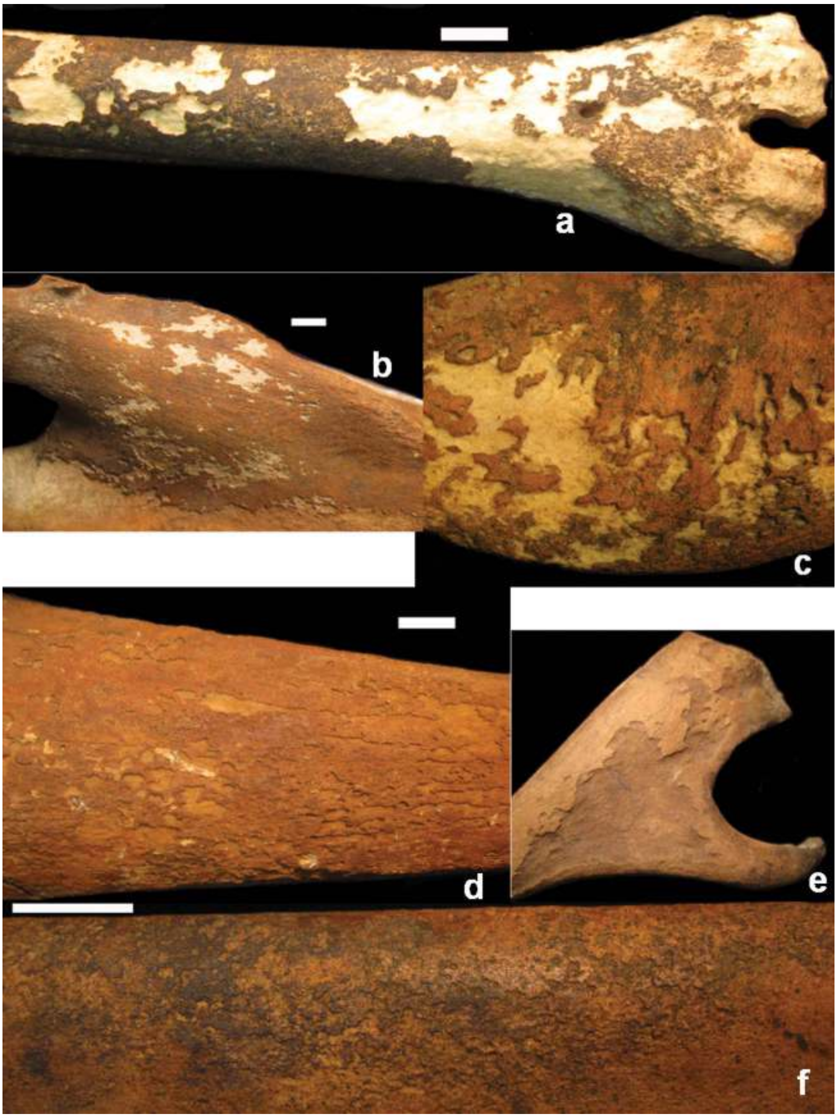

Figure 6.1 Acid-etched bones from Levelock Creek, Alaska. The creek is acidic because of acids leaching out of the surrounding tundra: (a) caribou (*Rangifer tarandus*) metatarsal showing deep cortical bone erosion, (b) caribou antler depicting shallow continuous cortical bone removal, (c) caribou dentary with deep discontinuous cortical bone erosion, (d) shallow discontinuous erosion pits on a rib, (e) surficial incipient erosion pits on cortical bone, and (f) extensively developed disconnected pitting on a diaphysis. Scale bars are 1 cm.

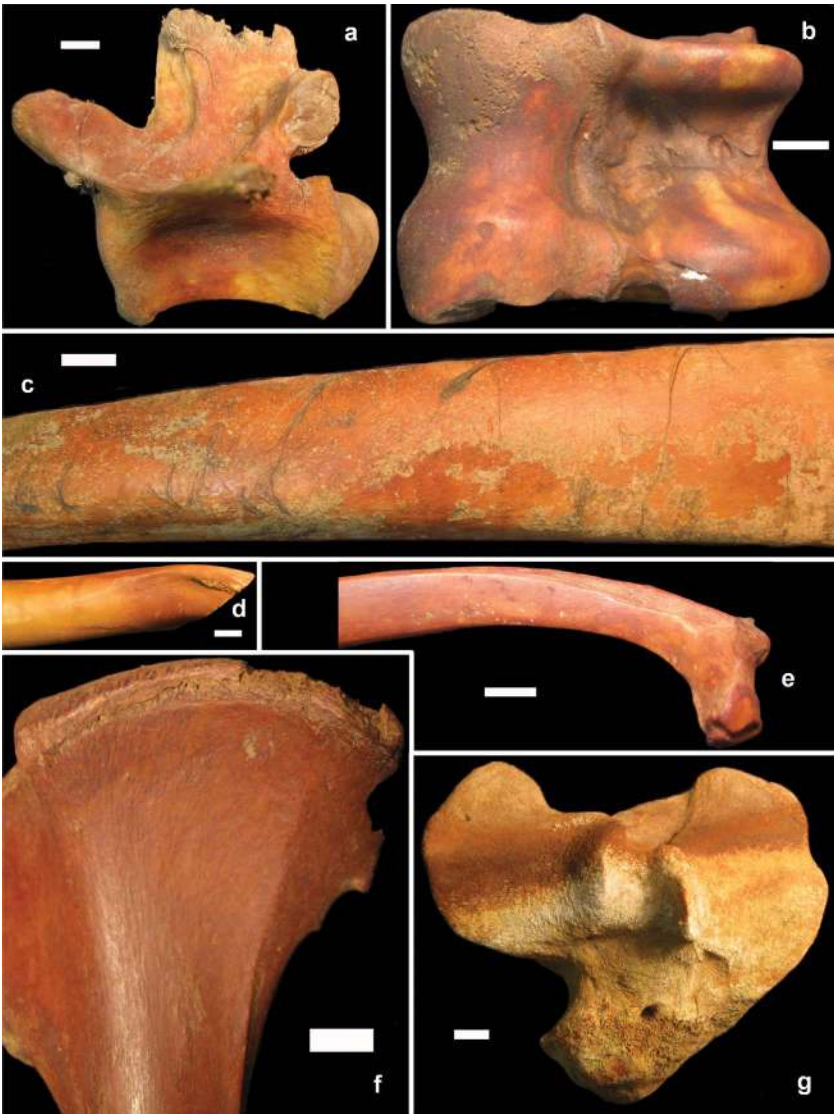

Figure 6.2 (a) Alligator (*Alligator mississippiensis*) bone that discolored during a 1-year residence in a river, (b) astragalus showing discoloration and incipient acid dissolution, (c) a rib shaft with discoloration and aquatic vegetation adhering to the bone surface, (d) sawn diaphysis with discoloration, (e) rib with deep reddish discoloration, (f) ilium with uniform brownish discoloration, and (g) proximal tibia showing bands of discoloration, likely caused by partial burial in a river. Scale bars are 1 cm.

burial in a river bed or through submersion in discolored water (Nawrocki et al. 1997; pers. obs.). A light green staining often accompanies the growth of algae on bone surfaces (Nawrocki et al. 1997; pers. obs.), a modification that can be found on bones in nearly all rivers and which can occur in less than a year (pers. obs.). Black staining has been observed often in conjunction with adipocere formation, which is usually found in small cavities in the bone (Figure 6.3) (Delabarde et al. 2013). Yellow staining appears to be the consequence of fat leaching out of the bone, discoloring its surface (Chapters 7 and 12). Figure 6.2 displays bones recovered from two rivers, all with discoloration.

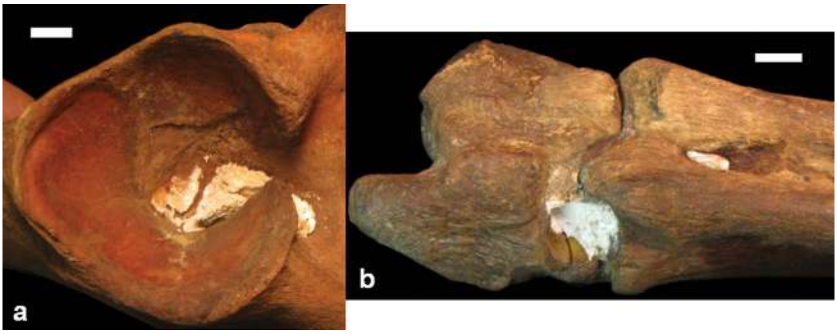

Figure 6.3 Location of adipocere formation. Adipocere, when preset, is often found in confined spaces (foramina, medullary cavity, articular fossae, etc.): (a) adipocere formation in an acetabular fossa, and (b) adipocere formation in spaces between bones as well as in a nutrient foramen. Scale bars are 1 cm.

Figure 6.4 Invertebrate casings can be of many shapes and sizes: (a) shows a calcified shell in a bone depression, and (b) shows a series of thin larval casings. Scale bar is 1 cm.

Invertebrate consumption of bone and larval casings are frequent fluvial taphonomic indicators. Larval boring appears as smooth-walled troughs, approximately U-shaped in cross-section, and often meandering. At times, feeding traces can be confused with acid etching. Generally, feeding traces are much smoother, deeper, regular, and sinuous than the irregular pitting of acid etching (Chapter 18). It should be noted that both acid etching and invertebrate feeding traces can be found on the same bone. Figure 6.4 displays bones recovered from an Alaska river with evident invertebrate casings.

Sediment and foraminifera impaction within cracks and hollow spaces is common in bones recovered from sandy or coarse bed rivers (Figure 6.5; DeBattista et al. 2013). The size, composition, and variety of clasts will be a function of the river from which the remains came; however, impacted sediment on or in a bone is a good indicator of some aqueous history, freshwater or marine (Chapter 7). If sand or gravel grains are wedged in cracks or holes in bones, it can suggest a fluvial origin, since there are few processes operating in a standing body of water (lake or pond) that can wedge sediment into openings (Nawrocki et al. 1997). Figure 6.5 shows sand impaction in bone cracks and foramina. It is possible that shrinking and swelling of bones through wetting and drying are the mechanisms causing clastic material to be wedged tightly in cracks and holes.

Bone cracking and warping from drying can occur when skeletal material is removed from (moving or still) water. While the focus of this review is modifications to bones from

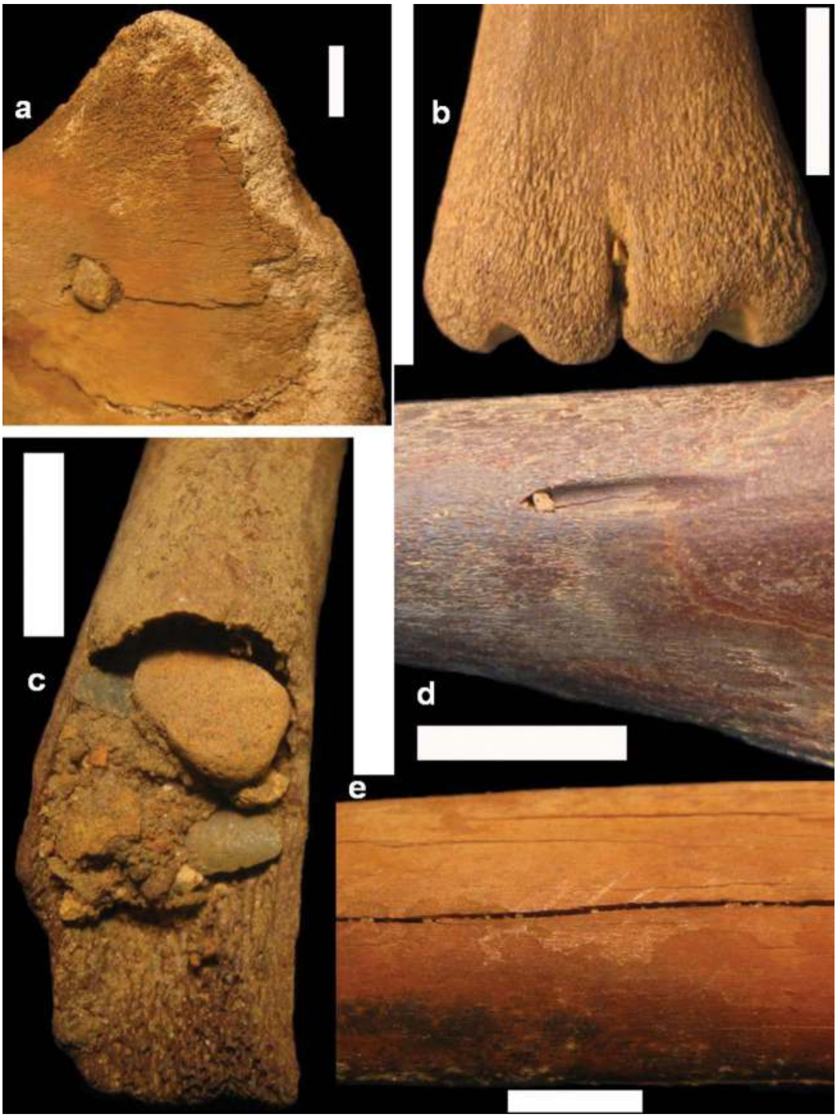

Figure 6.5 Sediment impaction in holes and cracks. Sediment is often found in small cracks or holes in bone: (a) grain of gravel pressed into an ilium while it was wet and pliable, (b) sand grain wedged in the slot between two fused metatarsals, (c) sand and gravel in a diaphysis, (d) sand grain wedged into a nutrient foramen, and (e) sand grains firmly fixed in a crack in cortical bone. Scale bars are 1 cm.

fluvial taphonomic processes, it should be noted that taphonomic modifications also occur on bones when removed from fluvial systems. The most obvious change is the drying of bones either during transport or in the laboratory. Drying often causes bones to contract, which causes extensional stresses along the exterior cortical bone surfaces, particularly on long bone (humeri, radii, ulnae, femora, tibiae, or fibulae) diaphyses. The result is often an elongate and deep crack (or cracks) extending from the exterior cortical bone into the medullary cavity often over nearly the entire length of a diaphysis (Figure 6.6). During drying of thousands of bones for experimentation, the author has observed that hundreds

Figure 6.6 Drying cracks. All cracks formed as bones dried: (a) juvenile ilium illustrating both small and large drying cracks, (b) close up of the deepest crack in the ilium from (a), (c) crack in the anterior surface of a metacarpal shaft, (d) sawed end of a rib demonstrating the degree of cracking and warping of cortical bone during drying, (e) elongate drying crack in a tibia that extends the length of the bone and penetrates the medullary cavity, and (f) two cracks deforming the surface of a rib, causing the bone to deflect outward. Scale bars are 1 cm.

of long bones crack, often violently and with a sharp, loud, startling, popping sound. (See also Prassack 2011 for a discussion of bone cracking during drying.) In addition to deep cracking, drying can alter the shape of skeletal material. When bones are wet, they are flexible to varying degrees. As a bone dries, it loses this flexibility and will retain the shape it was in during drying. Consequently, it is possible to bend or flex a bone while wet and dry it in a new, altered shape. This flexing is readily observable in scapulae, which can flex considerably while wet (Figure 6.7). When observing skeletal material recovered from fluvial

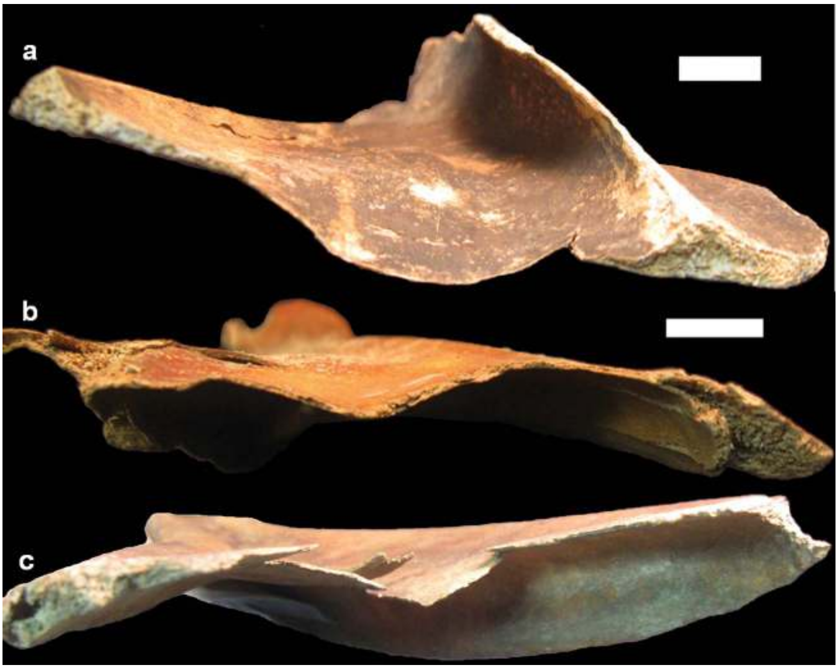

Figure 6.7 Scapulae deformation: (a) medially warped superior scapular border, (b) laterally warped superior scapular border, and (c) warped and cracked superior scapular border illustrating that bone can deform both medially and laterally simultaneously. Scale bars are 1 cm.

systems, it is important to remember that any large cracking and some bending may be a function of fluvial residence and removal, rather than some other taphonomic processes.

Analytical Techniques

Six methods have been proposed to identify skeletal assemblages that have experienced fluvial transport: Voorhies Groups (Voorhies 1969), equivalent particle diameters (Behrensmeyer 1973, 1975), relative transport potentials (Hanson 1980), transport index (Frison and Todd 1986; Trapani 1996, 1998), mobility numbers (Pavlish et al. 2002), and observing bones in preferred orientations (Lyman 1994; Voorhies 1969). When subjected to validation, none of these techniques were successful in predicting the observed bone transport in river systems (Evans 2015); as such, these methods have unknown applicability to skeletal assemblages. However, it is useful to understand them, because the fluvial taphonomy literature is full of references to these techniques, so each will be discussed in turn.

Voorhies (1969:69, Table 6.12) divided bones into slow-, medium-, and fast-moving groups, based upon flume experiments with coyote (*Canis latrans*) and sheep (*Ovis aries*) skeletons. Behrensmeyer (1973, 1975) continued the grouping of bones based on transport behavior and coined the term "*Voorhies Groups*," meaning grouping bones based on their relative transport rates. Since the term has never been precisely defined, some authors have generated between two and five different transport groups, depending on their method of study (settling column, flume, etc.) and the behavior of the bones that they studied. This method assumes that bones have consistent relative transport rates, and subsequent research has demonstrated that bones display many different rates of transport relative to each other (Aslan and Behrensmeyer 1996; Boaz and Behrensmeyer 1976; Dodson 1973; Evans 2015: Kaufman et al. 2011; Korth 1978; Morden 1991a; Trapani 1996, 1998), which falsifies the underlying assumption required for the method to work.

Behrensmeyer (1973, 1975) developed an equation that roughly equates bone transport potential with the transport potential of a spherical quartz grain with the same settling velocity. The hypothesis is that by comparing the grain size on or in which bones are deposited, a transported bone assemblage can be identified. If the quartz equivalent diameters of the bones are roughly equivalent to the grain size diameters of the surrounding sediment, then the bones were likely transported and deposited with the sediment; however, if the predicted grain size and the sediment size are different, then some other transport and deposition history is likely for the skeletal material. Since being proposed, some research has suggested that this oversimplified model is incorrect (Gifford 1977; Gifford and Behrensmeyer 1977; Trapani 1996), and when tested the method was not successful in predicting the transport and deposition of bones in rivers (Evans 2015). Moreover, an assumption of this method is that the settling velocity of bones remains constant, which is false, based on our understanding of bone bulk density changes due to degreasing, decay, and hydration over time (see “Bone Floatation and Saturation” section, above).

Hanson (1980:164–170) developed an equation for a dimensionless number proportional to the relative transport rate of skeletal material in a fluvial system. Since fluvial systems are complex with far too many variables to model simply, he made a few simplifying assumptions in the development of his equation. As a result, it is unclear how applicable the final equation is to the transport of bones in rivers. He then tested his equation by using it to calculate the relative transport potential of bones and compared the observed transport properties of bones in a flume to those predicted by his equation. A scatter plot (Hanson 1980:171, Figure 9.5) shows a rough trend suggesting a general correlation between transport potential and his dimensionless variable, but there is significant overlap of transport behaviors across the entire figure, suggesting that the method does not work reliably enough to use in casework. Moreover, his model does not account for changes in bone density over time or interactions with the bed, which are primary drivers of bone transport (Evans 2015).

Frison and Todd (1986) proposed the Fluvial Transport Index, a dimensionless number that describes the relative dispersal potential of skeletal remains. It is a descriptive tool that can be applied to an assemblage with known transport distances downstream. This method requires further validation, and its reliance upon known transport distances makes its application to forensic situations limited, given that this information is usually unknown. It also suffers from the same problems as other methods that do not account for bone bulk density changes over time.

Pavlish et al. (2002) proposed “mobility numbers,” which are dimensionless numbers that may be proportional to the relative transport potentials of different bones (similar to Hanson 1980). In a small-scale assessment of the method, Pavlish et al. (2002:235, Figure 6.2) plotted the relative distance traveled versus mobility number and found a general correlation between transport distance and mobility number, although there was a wide spread in the data. The spread in the data suggests that the tool does not have sufficient resolution to be useful in a forensic context, and it also does not factor in bone bulk density changes over time.

It has been suggested that skeletal assemblages that have experienced fluvial transport or reorientation can be identified by measuring and plotting the orientations of bones in the assemblage. This method assumes that bones consistently adopt a known and recognizable preferred orientation relative to a flow and that full disarticulation did not occur until after final deposition (i.e., that the elements did not reach their final location as part of an articulated unit with a different combined shape and density). Field data demonstrated that the orientation of skeletal material is largely a function of bed orientation (Evans 2015) in addition to flow direction. Consequently, bone orientations are not a reliable indicator of interactions between bones and a fluid flow, so is not a forensically useful technique.

Sheet Flow

There are many ways in which bones can enter a river, including the action of *sheet flow* over land surfaces during rainfall events. Sheet flow is the movement of shallow sheets of water over land surfaces until the fluid and their transported objects reach gullies or other channels in which they can be entrained in channelized flow. This mechanism may be more important than previously expected, because the importance of bone floatation was not understood. Most bones laying on the ground rapidly dry, degrease, and reduce in density. When confronted by even a shallow flow, they are likely to float, roll, or drag along the landscape unless caught on something.

Generally, bones on mild slopes do not move quickly (Andrews and Whybrow 2005; Frostick and Reid 1983), although bones in small depressions parallel to slope move faster than bones on featureless surfaces (Frostick and Reid 1983). Spherical- and rod-shaped bones move downslope faster than blade- or disk-shaped bones (Frostick and Reid 1983; Pokines et al. 2011). Similarly, larger, denser bones move downslope slower than smaller, lighter bones (Andrews 1990:17; Baker 2004), and saturated bones move less than dry bones, which may float on water or water and sediment mixtures (Woodruff and Varricchio 2011). When surface flow entrains sediment and bones, there is a higher likelihood of bone breakage (Woodruff and Varricchio 2008, 2011). It has been suggested that a higher land surface slope and higher water discharge will move material downstream faster (Frostick and Reid 1983). While this seems logically sound, there are no published data to support this inference.

Recommendations for Human Remains Recovery

When searching for remains in rivers, it is recommended to look on the upstream sides of obstructions (woody debris, bridge piers, rocks, etc.) (Nawrocki and Baker 2001; Young 1989; Evans 2010, 2015; Hanson 1980; Schick 1984, 1986), in eddies behind obstructions (Evans 2015; Schick 1984, 1986), on bars (of any kind: lateral, point, median, etc.; Behrensmeyer 1982; Evans 2015; Nawrocki et al. 1997), and to focus the search on the same side of the river as the body/parts entered (if known). All locations with drops in flow velocity (competence) should be searched, including banks, the upstream and lateral edges of deeper pools, and the edges of large bedforms (Aslan and Behrensmeyer 1987, 1996; Evans 2010, 2015; Schick 1984, 1986). Deep pools in channels not associated with debris are less likely to capture remains. Woody debris is particularly effective at catching and retaining remains (Evans 2007, 2015), so all woody debris should be searched thoroughly. One should also search for bodies both up- and downstream in rivers with significant shipping traffic or tidal influence. If a body entered a waterway, it may be useful to contact jurisdictions downstream to determine if they have found any remains. Conversely, if remains are found, it may be useful to contact upstream jurisdictions to determine if they have missing persons. Remains can and do float; so, search rivers all the way up to the high-water mark of the last flood; remains and bones can be found stuck in bushes and trees that were deposited during floods (Evans 2015)! Because remains are buried and uncovered periodically, repeat searches before and after high-flow events; some remains may be uncovered and transported during high flow. Hard or difficult to access locations can be searched using a waterproof camera (e.g. GoPro) attached to a pole. In addition, cadaver dogs can be used to facilitate searches, particularly of fleshed-out remains (Osterkamp 2011). In some locations, the local river fauna can be used to generally locate remains (Simões 2018), though this is a technique in its infancy.

When searching for skeletal material in fluvial systems, the reader should be aware that it is most common to find larger bones and miss many smaller skeletal elements (Aslan and Behrensmeyer 1996; Evans 2010). Small bones can be caught in any location with a space large enough to hold them (between rocks, vegetation, or woody debris), so if searching for small bones, one should look in the spaces between material in and on the bed. It is noteworthy that skeletal material can be found in rivers, if a search is implemented, often with a potential of high recovery rates (Aslan and Behrensmeyer 1996; Schick 1984, 1986; pers. obs.). Increasing the search effort may not yield large gains in bone recovery, since smaller material may have been transported away, or buried, causing them to be increasingly difficult to locate and recover. To find smaller remains, or parts that may not be obvious to a lay observer, invite students with osteology training (e.g., archaeology, paleontology, premedical) and teachers out to join the search. They have experience identifying bones in many orientations so are likely to find more remains than individuals in law enforcement with limited training in remains identification. This is an excellent way to improve recovery rates of remains, train students, and forge strong relationships between universities and law enforcement.

Conclusions

Presently, our understanding of fluvial taphonomic processes is in its infancy; thus, describing suites of taphonomic characters (*taphofacies*) expected from different river types is premature. Every river that the author has surveyed (n = 13) has yielded a different suite of taphonomic modifications on the remains found in the channel. Consequently, no one taphofacies model will suffice for "fluvial systems." What we understand about decay in river systems is largely anecdotal, and most of the research that has been performed has been on a small scale, so the variability in decay processes across different river environments is poorly understood. Similarly, transport of both full bodies and articulated parts in fluvial systems suffers from a lack of systematic, large-scale research, since most of what we know comes from isolated observations.

Comparatively, there is far more research concerning the transport and deposition of isolated (nonhuman) skeletal elements in fluvial systems. Unfortunately, the topic is far more complicated than studying the transport of standard geologic clasts (rocks, sand, etc.), since bones change shape, density, and articulation during decay and transport, and the size, sex, age, and body mass of the living organism also may affect bone transport dynamics. Shape changes occur through breakage and abrasion, while density alterations take place due to loss of grease, decay (buildup and loss of decay gases), water uptake, breakage, and abrasion. Aside from their clast properties continually changing, bones are periodically buried (partially or completely) and become fixed (armored or imbricated) in riverbeds. All these factors yield inconsistent or episodic transport, which is difficult to predict or even describe. As a result, the taphonomic modifications to bones and skeletal assemblages are difficult to interpret since the process of fluvial transport is so complicated, variable, and convoluted. While highly transportable bones (small, light, less dense bones) are rapidly moved and winnowed, these are the same bones that are most easily destroyed by other taphonomic processes or buried. Consequently, correctly interpreting the taphonomic modifications to bones and skeletal assemblages in fluviatile systems is difficult at best in theory and often cryptic in practice. Often, the analyst must consider many taphonomic processes operating sequentially and/or concurrently in potentially many different microenvironments that change over time. Since fluvial processes are so variable, there is a massive variability in taphonomic modifications found on remains that have experienced fluvial environments.

References

Alley, O. A. (2007) *Aquatic Decomposition in Chlorinated and Freshwater Environments*. M.S. Thesis, Texas State University, San Marcos, TX.

Amadasi, A., A. Camici, L. Sironi, A. Profumo, D. Merli, D. Mazzarelli, D. Porta, H. Duday, and C. Cattaneo (2015) The effects of acid and alkaline solutions on cut marks and on the structure of bone: An experimental study on porcine ribs. *Legal Medicine* 17:503–508.

Andrews, P. (1990) *Owls, Caves and Fossils*. University of Chicago Press, Chicago.

Andrews, P., and P. Whybrow (2005) Taphonomic observations on a camel skeleton in a desert environment in Abu Dhabi. *Palaeontologia Electronica* 8:1–17.

Aslan, A., and A. K. Behrensmeyer (1987) Vertebrate taphonomy in the East Fork River, Wyoming. *Geological Society of America Abstracts with Programs* 19:575.

Aslan, A., and A. K. Behrensmeyer (1996) Taphonomy and time resolution of bone assemblages in a contemporary fluvial system: The East Fork River, Wyoming. *Palaios* 11:411–421.

Ayers, L. E. (2010) *Differential Decomposition in Terrestrial, Freshwater, and Saltwater Environments; A Pilot Study*. M.S. Thesis, Texas State University, San Marcos, TX.

Baker, A. J. (2004) *A Taphonomic Analysis of Human Cremains from the Fox Hollow Farm Serial Homicide Site*. M.S. Thesis, University of Indianapolis, Indianapolis, IN.

Barrios, M., and M. Wolff (2011) Initial study of arthropods succession and pig carrion decomposition in two freshwater ecosystems in the Colombian Andes. *Forensic Science International* 212:164–172.

Bassett, H. E., and M. H. Manhein (2002) Fluvial transport of human remains in the lower Mississippi River. *Journal of Forensic Sciences* 47(4):1–6.

Becker, R. F. (2000) Mythos of underwater recovery operations. *FBI Law Enforcement Bulletin* September 2000:1–5.

Behrensmeyer, A. K. (1973) *The Taphonomy and Paleoecology of Plio-Pleistocene Vertebrate Assemblages East of Lake Rudolf, Kenya*. Ph.D. Dissertation, Harvard University, Cambridge, MA.

Behrensmeyer, A. K. (1975) The taphonomy and paleoecology of Plio-Pleistocene vertebrate assemblages of Lake Rudolf, Kenya. *Bulletin of the Museum of Comparative Zoology* 146:473–578.

Behrensmeyer, A. K. (1982) Time resolution in fluvial vertebrate assemblages. *Paleobiology* 8(3):211–227.

Behrensmeyer, A. K. (1990) Bones. In *Paleobiology: A Synthesis* ed. by D. E. G. Briggs and P. R. Crowther, pp. 232–235. Blackwell Scientific Publications, Oxford.

Behrensmeyer, A. K. (1991) Terrestrial vertebrate accumulations. In *Taphonomy: Releasing the Data Locked in the Fossil Record* ed. by P. A. Allison and D. E. G. Briggs, pp. 291–335. Plenum, New York.

Behrensmeyer, A. K., K. D. Gordon, and G. T. Yanagi (1989) Nonhuman bone modification in Miocene fossils from Pakistan. In *Bone Modification* ed. by R. Bonnichsen and M. H. Sorg, pp. 99–120. Center for the Study of the First Americans, Orono, ME.

Benbow, M. E., J. L Pechal, J. M. Lang, R. Erb, and J. R. Wallace (2015) The potential of high-throughput metagenomic sequencing of aquatic bacterial communities to estimate the post-mortem submersion interval. *Journal of Forensic Sciences* 60(6):1500–1510.

Berryman, H. E., J. O. Potter, and S. Oliver (1988) The ill-fated passenger steamer *Sultana*: An inland maritime mass disaster of unparalleled magnitude. *Journal of Forensic Sciences* 33(3):842–850.

Bickart, K. J. (1984) A field experiment in avian taphonomy. *Journal of Vertebrate Paleontology* 4(4):525–535.

Blanco Pampín, J., and B. A. López-Abajo Rodríguez (2001) Surprising drifting of bodies along the coast of Portugal and Spain. *Legal Medicine* 3(3):177–182.

Blob, R. W. (1997) Relative hydrodynamic dispersal potentials of soft-shelled turtle elements: Implications for interpreting skeletal sorting in assemblages of non-mammalian terrestrial vertebrates. *Palaios* 12:151–164.

Boaz, D. D. (1982) *Modern Riverine Taphonomy: Its Relevance to the Interpretation of Plio-Pleistocene Hominid Paleoecology in the Omo Basin, Ethiopia*. Ph.D. Dissertation, University of California, Berkeley, CA.

Boaz, N. T., and A. K. Behrensmeyer (1976) Hominid taphonomy: Transport of human skeletal parts in an artificial fluviatile environment. *American Journal of Physical Anthropology* 45(1):53–60.

Brady, M. (2005) *An Experimental and Field-Based Approach to the Taphonomy of Microvertebrate Assemblages: A Case Study in the Judith River Formation of North-Central Montana*. Senior Thesis, Macalester College, St. Paul, MN.

Brady, M., and R. Rogers (2005) An experimental and field-based approach to microvertebrate bonebed taphonomy in the Judith River Formation of north-central Montana. *Geological Society of America Abstracts with Programs* 37:24.

Brady, M., and R. Rogers (2007) Exploring the origins of microfossil bonebeds. *Journal of Vertebrate Paleontology* 27:52A.

Brady, T. V. (2012) The case of the frustrating floater. *Proceedings of the American Academy of Forensic Sciences* 18:273.

Brewer, V. B. (2005) Observed taphonomic changes and drift trajectory of bodies recovered from the tidal Thames, London England: A 15-year retrospective study. *Proceedings of the American Academy of Forensic Sciences* 11:286.

Bromage, T. G. (1984) Interpretation of scanning electron microscopic images of abraded forming bone surfaces. *American Journal of Physical Anthropology* 64(2):161–178.

Brooks, S., and R. H. Brooks (1984) Effects on bone of abrasive contents in moving water. *Abstracts from the First International Conference on Bone Modification*, Carson City, NV, August 17–19, 1984:6–7.

Brooks, S., and R. H. Brooks (1997) The taphonomic effects of flood waters on bone. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 553–558. CRC Press, Boca Raton, FL.

Brusven, M. A., and A. C. Scoggan (1969) Sarcophagous habits of Trichoptera larvae on dead fish. *Entomological News* 80:103–105.

Burke, T. W., and C. E. O'Rear (1998) Forensic diving, the latest in underwater investigation. *FBI Law Enforcement Bulletin* April 1998:1–8.

Butler, V. L. (1987) Distinguishing natural from cultural salmonid deposits in the Pacific Northwest of North America. In *Natural Formation Processes and the Archaeological Record* ed. by D. T. Nash and M. D. Petraglia, pp. 131–149. British Archaeological Reports, International Series 352, Oxford.

Byard, R. W. (2018) Putrefaction: An additional complicating factor in the assessment of freshwater drownings in rivers. *Journal of Forensic Sciences* 63(3):899–901.

Casamatta, D. A., and R. G. Verb (2000) Algal colonization of submerged carcasses in a mid-order woodland stream. *Journal of Forensic Sciences* 45(6):1280–1285.

Cederholm, C. J., and N. P. Peterson (1985) The retention of coho salmon (*Oncorhynchus kisutch*) carcasses by organic debris in small streams. *Canadian Journal of Fisheries and Aquatic Sciences* 42(6):1222–1225.

Cederholm, C. J., D. B. Houston, D. L. Cole, and W. J. Scarlett (1989) Fate of coho salmon (*Oncorhynchus kisutch*) carcasses in spawning streams. *Canadian Journal of Fisheries and Aquatic Sciences* 46(8):1347–1355.

Cederholm, C. J., M. D. Kunze, T. Murota, and A. Sibatani (1999) Pacific salmon carcasses: Essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. *Fisheries* 24(1):6–15.

Chaloner, D. T., M. S. Wipfli, and J. P. Caouette (2002) Mass loss and macroinvertebrate colonization of Pacific salmon carcasses in south-eastern Alaskan streams. *Freshwater Biology* 47(2):263–273.

Christensen, A. M., and S. W. Meyers (2011) Macroscopic observations of the effects of varying fresh water pH on bone. *Journal of Forensic Sciences* 56(2):475–479.

Cleason, S., J. Li, J. Compton, and P. Bisson (2006) Response of nutrients, biofilm, and benthic insects to salmon carcass addition. *Canadian Journal of Fisheries and Aquatic Sciences* 63(6):1230–1241.

Coard, R. (1999) One bone, two bones, wet bones, dry bones: Transport potentials under experimental conditions. *Journal of Archaeological Science* 26(11):1369–1375.

Coard, R., and R. W. Dennell (1995) Taphonomy of some articulated skeletal remains; transport potential in an artificial environment. *Journal of Archaeological Science* 22(3):441–448.

Collins, B. R. (2010) Element survivability of *Salmo salar*. *Journal of Taphonomy* 8(4):291–300.

Corbat, M., M. Giardina, and A. Zangrando (2017) The influence of fish bone morphology on aquatic transport: An experimental approach through elements of Creole perch (Percichthyidae: *Perichthys trucha*; [Valenciennes, 1833]). *Journal of Archaeological Science: Reports* 14:252–261.

D'Alonzo, S. S., S. J. Clinkinbeard, and E. J. Bartelink (2012) Fluvial transport of human remains in the Sacramento River, California. *Proceedings of the American Academy of Forensic Sciences* 18:408–409.

Darwin, C. R. (1839) *Narrative of the Surveying Voyages of His Majesty's Ships Adventure and Beagle Between the Years 1826 and 1836: Describing Their Examination of the Southern Shores of South America, and the Beagle's Circumnavigation of the Globe*. H. Colburn, London.

De Donno, A., C. P. Campobasso, V. Santoro, S. Leonardi, S. Tafuri, and F. Introna (2014) Bodies in sequestered and non-sequestered aquatic environments: A comparative taphonomic study using decompositional scoring system. *Science and Justice* 54(6):439–446.

DeBattista, R., T. J. R. Thompson, C.E.L. Thompson, and R. L. Gowland (2013) A comparison of surface features on submerged and non-submerged bone using scanning electron microscopy. *Journal of Forensic and Legal Medicine* 20(6):770–776.

Delabarde, T., C. Keyser, A. Tracqui, D. Charabidze, and B. Ludes (2013) The potential of forensic analysis on human bones found in riverine environment. *Forensic Science International* 228:e1–e5.

Dilen, D. R. (1984) The motion of floating and submerged objects in the Chattahoochee River, Atlanta, GA. *Journal of Forensic Sciences* 29(4):1027–1037.

Doberentz, E., and B. Madea (2010) Estimating the time of immersion of bodies found in water—An evaluation of a common method to estimate the minimum time interval of immersion. *Revista Espanola De Medicina Legal* 36(2):51–61.

Dodson, P. (1973) The significance of small bones in paleoecological interpretation. *University of Wyoming Contributions to Geology* 12(1):15–19.

Domínguez-Rodrigo, M., L. Cobo-Sánchez, J. Yravedra, D. Uribelarrea del Val, C. Arriaza, E. Organista, and E. Baquedano (2018) Fluvial spatial taphonomy: A new method for the study of post-depositional processes. *Archaeological and Anthropological Sciences* 10(7): 1769–1789.

Donoghue, E. R., and S. C. Minnigerode (1977) Human body buoyancy: A study of 98 men. *Journal of Forensic Sciences* 22(3):573–579.

Duband, S., F. Forest, Y. Gaillard, J.-M. Dumollard, M. Debout, and M. Peoc'h (2011) Macroscopic histological and toxicological aspects of early *Gammarus pulex* scavenging. *Forensic Science International* 209:e16–e22.

Duckworth, W. L. H. (1904) Note on the dispersive power of running water on skeletons: With particular reference to the skeletal remains of *Pithecanthropus Erectus*. In *Studies from the Anthropological Laboratory, the Anatomy School, Cambridge* ed. by W. L. H. Duckworth, pp. 274–277. Cambridge University Press, Cambridge.

Dutelle, A. (2007) Underwater crime-scene response, part 1 of 2: Underwater investigative teams. *Evidence Technology Magazine* 5:24–27.

Elder, R. L. (1985) *Principles of Aquatic Taphonomy with Examples from the Fossil Record*. Ph.D. Dissertation, University of Michigan, Ann Arbor, MI.

Evans, T. (2006) Fluvial transport of bones: Our state of knowledge and future research directions. *Proceedings of the American Academy of Forensic Sciences* 12:173.

Evans, T. (2007) Field observations of bone deposition in six rivers. *Proceedings of the American Academy of Forensic Sciences* 13:207.

Evans, T. (2010) Pilot fluvial skeletal transport experiments. *Geological Society of America Abstracts with Programs* 42:28.

Evans, T. (2015) *A Critical Evaluation of Our Understanding of Bone Transport and Deposition in Fluvial Channels*. Ph.D. Dissertation, Montana State University, Bozeman, MT.

Falkenthal, G. (1999) Underwater search and recovery team: A passion for diving and a desire to serve. *Law Enforcement Quarterly* 82:20–23.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Frison, G. C., and L. C. Todd (1986) *The Colby Mammoth Site: Taphonomy and Archaeology of a Clovis Kill in Northern Wyoming*. University of New Mexico Press, Albuquerque, NM.

Frostick, L., and I. Reid (1983) Taphonomic significance of sub-aerial transport of vertebrate fossils on steep semi-arid slopes. *Lethaia* 16(2):157–164.

Gifford, D. P. (1977) *Observations of Modern Human Settlements as an Aid to Archaeological Interpretation*. Ph.D. Dissertation, University of California, Berkeley, CA.

Gifford, D. P. (1981) Taphonomy and paleoecology: A critical review of archaeology's sister disciplines. *Advances in Archaeological Method and Theory* 4:365–438.

Gifford, D. P., and A. K. Behrensmeyer (1977) Observed formation and burial of a recent human occupation site in Kenya. *Quaternary Research* 8(3):245–266.

Glassey, S. (2014) *Swiftwater Body Recovery, Student Manual* (2nd ed.). Public Safety Institute (New Zealand), Wellington.

Glock, J. W., G. Hartman, and L. Conquest (1980) *Skagit River Chum Salmon Carcass Drift Study*. City Light Department, City of Seattle, WA.

Gnidovec, D. M. (1978) *Taphonomy of the Powder Wash Vertebrate Quarry, Green River Formation (Eocene), Uintah County, Utah*. M.S. Thesis, Fort Hays State University, Hays, KS.

Goff, M. L., and C. B. Odom (1987) Forensic entomology in the Hawaiian islands: Three case studies. *American Journal of Forensic Medicine and Pathology* 8:45–50.

Griffith, S., C. Thompson, T. Thompson, and R. Gowland (2016) Experimental abrasion of water submerged bone: The influence of bombardment by different sediment classes on microablation rate. *Journal of Archaeological Science: Reports* 10:15–29.

Guatame-Garcia, A. C., L. A. Camacho, and T. Simmons (2008) Computer simulation for drift trajectories of objects in the Magdalena River, Colombia. *Proceedings of the American Academy of Forensic Sciences* 14:319–320.

Gutierrez, M. A., and C. A. Kaufmann (2007) Criteria for the identification of formation processes in guanaco (*Lama guanicoe*) bone assemblages in fluvial-lacustrine environments. *Journal of Taphonomy* 5(4):151–176.

Haefner, J. N., J. R. Wallace, and R. W. Merritt (2002) A new technique to estimate a postmortem submersion interval (PMSI) using algal growth rates. *Proceedings of the American Academy of Forensic Sciences* 8:184–185.

Haefner, J. N., J. R. Wallace, and R. W. Merritt (2004) Pig decomposition in lotic aquatic systems: The potential use of algal growth in establishing a postmortem submersion interval (PMSI). *Journal of Forensic Sciences* 49(2):330–336.

Haglund, W. D. (1993) Disappearance of soft tissue and disarticulation of human remains from aqueous environments. *Journal of Forensic Sciences* 38(4):806–815.

Haglund, W. D., D. G. Reichert, and D. T. Reay (1990) Recovery of decomposed and skeletal human remains in the "Green River Murder" investigation: Implications for medical examiner/coroner and police. *American Journal of Forensic Medicine and Pathology* 11(1):35–43.

Haglund, W. D., and M. H. Sorg (2002) Human remains in water environments. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 201–218. CRC Press, Boca Raton, FL.

Hanson, C. B. (1980) Fluvial taphonomic processes: Models and experiments. In *Fossils in the Making* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 156–181. University of Chicago Press, Chicago.

Harnett, K. M., L. C. Fulginiti, and F. D. Modica (2011) The effects of corrosive substances on human bone, teeth, hair, nails and soft tissue. *Journal of Forensic Sciences* 56(4):954–959.

Haskell, N. H., D. G. McShaffrey, D. A. Hawley, R. E. Williams, and J. E. Pless (1989) Use of aquatic insects in determining submersion interval. *Journal of Forensic Sciences* 34(3):622–632.

Hawley, D. A., N. H. Haskell, D. G. McShaffrey, R. E. Williams, and J. E. Pless (1989) Identification of a red "fiber": Chironomid larvae. *Journal of Forensic Sciences* 34(3):617–621.

Heaton, V. G., A. Lagden, C. Moffatt, and T. Simmons (2010) Predicting the postmortem submersion interval for human remains recovered from U.K. waterways. *Journal of Forensic Sciences* 55(2):302–307.

Herrmann, N. P., B. Bassett, and L. M. Jantz (2004) High velocity fluvial transport: A case study from Tennessee. *Proceedings of the American Academy of Forensic Sciences* 10:282.

Hobischak, N. R. (1997a) *Freshwater Invertebrate Succession and Decompositional Studies on Carrion in British Columbia*. M.S. Thesis, Simon Fraser University, Burnaby, BC.

Hobischak, N. R. (1997b) Freshwater invertebrate succession and decompositional studies on carrion in British Columbia. Canadian Police Research Centre, TR-10-98, Ottawa, ON, Canada.

Hobischak, N. R., and G. S. Anderson (1999) Freshwater-related death investigations in British Columbia in 1995-1996. A review of coroners cases. *Canadian Society of Forensic Sciences Journal* 32:97–106.

Hobischak, N. R., and G. S. Anderson (2002) Time of submergence using aquatic invertebrate succession and decompositional changes. *Journal of Forensic Sciences* 47(1):142–151.

Kakizaki, E., S. Kozawa, H. Matsuda, E. Muraoka, T. Uchiyama, M. Sakai, and N. Yukawa (2010) Freshwater bacterioplankton cultured from liver, kidney and lungs of a decomposed cadaver retrieved from a sandy seashore: Possibility of drowning in a river and then floating out to sea. *Legal Medicine* 12(4):195–199.

Kaufmann, C., M. A. Gutierrez, M. C. Alvarez, M. E. Gonzalez, and A. Massigoge (2011) Fluvial dispersal potential of guanaco bones (*Lama guanicoe*) under controlled experimental conditions: The influence of age classes to the hydrodynamic behavior. *Journal of Archaeological Science* 38(2):334–344.

Keiper, J. B., and D. A. Casamatta (2001) Benthic organisms as forensic indicators. *Journal of the North American Benthological Society* 20(2):311–324.

Keiper, J. B., E. G. Chapman, and B. A. Foote (1997) Midge larvae (Diptera: *Chironomidae*) as indicators of postmortem submersion interval of carcasses in a woodland stream: A preliminary report. *Journal of Forensic Sciences* 42(6):1074–1079.

Kline, T. C., J. J. Goering, and R. J. Piorkowski (1997) The effect of salmon carcasses on Alaskan freshwaters. In *Freshwaters of Alaska: Ecological Syntheses* ed. by A. M. Milner and M. W. Oswood, pp. 179–204. Springer-Verlag, New York.

Knell, M. (2009) Experiments in actualistic taphonomy using modern freshwater turtle remains for interpreting fossil turtle localities in fluvial depositional environments. *Journal of Vertebrate Paleontology* 29:128A.

Komar, D. A., and W. E. Potter (2007) Percentage of body recovered and its effect on identification rates and cause and manner of death determination. *Journal of Forensic Sciences* 52(3): 528–531.

Kontrovitz, M., and J. M. Slack (1991) Transport of human teeth: An experimental study. *Geological Society of America Abstracts with Programs* 23:253.

Korth, W. W. (1978) *Taphonomy of Microvertebrate Fossil Assemblages*. M.S. Thesis, University of Nebraska, Lincoln, NE.

Korth, W. W. (1979) Taphonomy of microvertebrate fossil assemblages. *Annals of the Carnegie Museum* 48:235–285.

Lang, J. M., R. Erb, J. L. Pechal, J. R. Wallace, R. W. McEwan, and M. E. Benbow (2016) Microbial biofilm community variation in flowing habitats: Potential utility as bioindicators of postmortem submersion intervals. *Microorganisms* 4(1):1–17.

Llona, A. C. P., and P. J. Andrews (1999) Amphibian taphonomy and its application to the fossil record of Dolina (Middle Pleistocene, Atapuerca, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology* 149:411–429.

Long, D. J., and M. R. Langer (1995) Nassariid gastropods as destructive agents in preservation and fossilization of marine fishes. *Experientia* 51(1):85–89.

Lyman, L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

MacDonell, N., and G. S. Anderson (1997) *Aquatic Forensics Determination of Time Since Submergence Using Aquatic Invertebrates*. Canadian Police Research Centre, Technical Report TR-09-97, Ottawa, ON, Canada.

Madea, B. (2002) Estimation of duration of immersion. *Nordisk Rettsmedisin* 8:4–10.

Madea, B., and E. Doberentz (2010) Comment on: Heaton V., Lagden A., Moffatt C. Simmons T., Predicting the postmortem submersion interval for human remains recovered from U.K. waterways. *Journal of Forensic Sciences* 55(6):1666–1667.

Mann, R. W., W. M. Bass, and L. Meadows (1990) Time since death and decomposition of the human body: Variables and observations in case and experimental field studies. *Journal of Forensic Sciences* 35(1):103–111.

McUne, E. L. and J. E. Gagnon (2007) Underwater body recovery procedures in adverse conditions. *Proceedings of the American Academy of Forensic Sciences* 13:206.

Medina, A. G., O. S. Hernando, and G. J. Rios (2015) The use of the developmental rate of the aquatic midge *Chironomus riparius* (Diptera, Chironomidae) in the assessment of the postsubmersion interval. *Journal of Forensic Sciences* 60(3):822–826.

Merritt, R. W., and J. R. Wallace (2001) The role of aquatic insects in forensic investigations. In *Forensic Entomology: The Utility of Arthropods in Legal Investigations* ed. by J. H. Byrd and J. L. Castner, pp. 177–222. CRC Press, Boca Raton, FL.

Middleton, G. V.; and J. B. Southard (1984) *Mechanics of Sediment Movement: Lecture Notes for Short Course No. 3* (2nd ed.). Society of Economic Paleontologists and Mineralogists, Tulsa, OK.

Minakawa, N. (1997) *The Dynamics of Aquatic Insect Communities Associated with Salmon Spawning*. Ph.D. Dissertation, University of Washington, Seattle, WA.

Minakawa, N., and R. I. Gara (2005) Spatial and temporal distribution of coho salmon carcasses in a stream in the Pacific Northwest, USA. *Hydrobiologia* 539:163–166.

Minshall, G. W., E. Hitchcock, and J. R. Barnes (1991) Decomposition of rainbow trout (*Oncorhynchus mykiss*) carcasses in a forest stream ecosystem inhabited by non-anadromous fish populations. *Canadian Journal of Fisheries and Aquatic Sciences* 48(2):191–195.

Moore, J. R., and D. J. Varricchio (2018) Taphonomic pathways in vertebrate fossil assemblages illustrated by a bovine mass drowning event. *Palaios* 33:174–184.

Moore, J., D. Varricchio, and F. Jackson (2008) Identifying taphonomic pathways in modern bone assemblages using ordination analysis. *Journal of Vertebrate Paleontology* 28:118A.

Morden, J. L. (1991a) *Hominid Taphonomy: Density, Fluvial Transport, and Carnivore Consumption of Human Remains with Application to Three Plio/Pleistocene Hominid Sites*. Ph.D. Dissertation, Rutgers University, Piscataway, NJ.

Morden, J. L. (1991b) Models of fluvial transport of human bones, with application to modern fossil hominid sites. *Journal of Vertebrate Paleontology* 11:47–48.

Mottonen, M., and M. Nuutila (1977) Postmortem injury caused by domestic animals, crustaceans, and fish. In *Forensic Medicine, A Study in Trauma and Environmental Hazards, Volume II Physical Trauma* ed. by C. G. Tedeschi, W. G. Eckert, and L. G. Tedeschi, pp. 1096–1098. W. B. Saunders, Philadelphia, PA.

Nawrocki, S. P., and A. Baker (2001) Fluvial transport of human remains at the Fox Hollow serial homicide site. *Proceedings of the American Academy of Forensic Sciences* 7:246–247.

Nawrocki, S. P., and J. E. Pless (1993) Transport of human remains in fluvial environments: A review. *Proceedings of the American Academy of Forensic Science* 1993:146.

Nawrocki, S. P., J. E. Pless, D. A. Hawley, and S. A. Wagner (1997) Fluvial transport of human crania. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 529–552. CRC Press, Boca Raton, FL.

Osterkamp, T. (2011) K9 water searches: Scent and scent transport considerations. *Journal of Forensic Sciences* 56(4):907–912.

Palazzo, C., G. Pelletti, P. Fias, R. Boscolo-Berto, F. Fersini, R. M. Gaudio, and S. Pelotti (2020) Postmortem submersion interval in human bodies recovered from fresh water in an area of Mediterranean climate. Application and comparison of preexisting models. *Forensic Science International* 306:1–6.

Palmer, C. (2020) Estimating the impact of laminar flow on the pattern and rate of decomposition in aquatic environments—Is there a better way of modeling decomposition? *Journal of Forensic Sciences* 65(5):1601–1609.

Pante, M. C., and R. J. Blumenschine (2009) Fluvial transport of hominin- and carnivore-modified long bone fragments. *Program of the Seventy-Eighth Annual Meeting of the American Association of Physical Anthropologists*, Chicago, pp. 286–287.

Pante, M. C., and R. J. Blumenschine (2010) Fluvial transport of bovid long bones fragmented by the feeding activities of hominins and carnivores. *Journal of Archaeological Science* 37:846–854.

Parker, G. (2006) Gary Parker's Morphodynamics Web Page. Electronic document, http://hydrolab.illinois.edu/people/parkerg/ accessed 2 February 2021.

Parmenter, R. R., and V. A. Lamarra (1991) Nutrient cycling in a freshwater marsh: The decomposition of fish and waterfowl carrion. *Limnology and Oceanography* 36(5):976–987.

Pascali, J. P., G. Viel, G. Cecchetto, N. Pigaiani, S. Vanin, M. Montisci, and P. Fais (2020) The Red Swamp crayfish *Procambarus Clarkii* (the Louisiana crayfish) as a particular scavenger on a human corpse. *Journal of Forensic Sciences* 65(1):323–326.

Pavlish, L. A., M. R. Kleindienst, and P. J. Sheppard (1998) Flume experiments with stone and bone. *Program and Abstracts of the 31st International Symposium on Archaeometry, Budapest,* 27 April–1 May 1998, p. 118.

Pavlish, L. A., M. R. Kleindienst, and P. J. Sheppard (2002) Flume experiments with stone and bone. In *Archaeometry 98* ed. by E. Jerem and K. T. Biro, pp. 231–237. British Archaeological Reports, International Series S1043, Oxford.

Perry, P. A. (2005) Human decomposition in the Detroit River. *Proceedings of the American Academy of Forensic Sciences* 11:285–286.

Petric, M. S., N. R. Hobischak, and G. S. Anderson (2004) Examination of factors surrounding human decomposition in freshwater: A review of body recoveries and coroner cases in British Columbia. *Canadian Society of Forensic Science Journal* 37(1):9–17.

Peyron, P., T. Casper, O. Mathieu, Y. Musizzano, and E. Baccino (2018) Complex suicide by self-stabbing and drowning: A case report and a review of literature. *Journal of Forensic Sciences* 63(2):598–601.

Piorkowski, R. J. (1995) *Ecological Effects of Spawning Salmon on Several Southcentral Alaskan Streams*. Ph.D. Dissertation, University of Washington, Seattle, WA.

Pokines, J. T., A. Nowell, M. S. Bisson, C. E. Cordova, and C. J. H. Ames (2011) The functioning of a natural faunal trap in a semi-arid environment: Preliminary investigations of WZM-1, a limestone sinkhole site near Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan. *Journal of Taphonomy* 9(2):89–115.

Prassack, K. A. (2011) The effect of weathering on bird bone survivorship in modern and fossil saline-alkaline lake environments. *Paleobiology* 37(4):633–654.

Rayo, J., G. Peral, and M. Bordas (2014) Primer studio sobre la reduccion cadeverica en condiciones sumergidas en la peninsula Iberica, empleando un modelo de cerdo domstico (*Sus scrofa* L., 1758) en el Rio Manzanares (Comunidad Autonoma de Madrid). *Ciencia Forense* 11:261–294.

Reh, H. (1967) Anhaltspunkte fur die Bestimmung der Wasserzeit. *Deutsche Zeitschrift fur die Gesamte Gerichtliche Medizin* 59:235–245.

Reh, H. (1969) *Diagnostik des Ertrinkungstodes und Bestimmung der Wasserzeit.* Michael Triltsch Verlag, Dusseldorf, Germany.

Reh, H., K. Haaroff, and C. D. Vogt (1977) Die Schatzung der Todeszeit bei Wasserleichen. *Zeitschrift fur Rechtsmedizin* 79:261–266.

Reijnen, G., H. T. Gelderman, B. F. Grotenbevelsborg, U. J. Reijnders, and W. L. Duijst (2018) The correlation between the Aquatic Decomposition Score (ADS) and the post-mortem submersion interval measured in Accumulated Degree Days (ADD) in bodies recovered from fresh water. *Forensic Science, Medicine and Pathology* 14(3):301–306.

Rodriguez, W. C. (1997) Decomposition of buried and submerged bodies. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 459–467. CRC Press, Boca Raton, FL.

Rogers, R. R. and S. M. Kidwell (2007) A conceptual framework for the genesis and analysis of vertebrate skeletal concentrations. In *Bonebeds, Genesis, Analysis and Paleobiological Significance* ed. by R. R. Rogers, D. A. Eberth, and A. R. Fiorillo, pp. 1–63. University of Chicago Press, Chicago.

Schick, K. D. (1984) *Processes of Palaeolithic Site Formation: An Experimental Study.* Ph.D. Dissertation, University of California, Berkeley, CA.

Schick, K. D. (1986) *Stone Age Sites in the Making: Experiments in the Formation and Transformation of Archaeological Occurrences.* British Archaeological Reports, International Series 319, Oxford.

Schick, K. D. (1987) Experimentally derived criteria for assessing hydrologic disturbance of archaeological sites. In *Natural Formation Processes and the Archaeological Record* ed. by D. T. Nash and M. D. Petraglia, pp. 86–107. British Archaeological Reports, International Series 352, Oxford.

Schuldt, J. A., and A. E. Hershey (1995) Effect of salmon carcass decomposition on Lake Superior tributary streams. *Journal of the North American Benthological Society* 14:259–268.

Seet, B. L. (2005) *Estimating the Postmortem Interval in Freshwater Environments.* M.S. Thesis, University of Tennessee, Knoxville, TN.

Shipman, P. (1981) *Life History of a Fossil.* Harvard University Press, Cambridge, MA.

Shipman, P., and J. J. Rose (1983) Early hominid hunting, butchering, and carcass processing behaviors: Approaches to the fossil record. *Journal of Anthropological Archaeology* 2:57–98.

Shipman, P., and J. J. Rose (1988) Bone tools: An experimental approach. In *Scanning Electron Microscopy in Archaeology* ed. by S. L. Olsen, pp. 303–335. British Archaeological Reports, International Series 452, Oxford.

Simões, E. L. (2018) Forensic use of the piracatinga fish (*Callophysius macropterus*) to locate and identify human remains retrieved from the Amazon River. *Journal of Forensic Sciences* 63(5):1587–1591.

Spennemann, D. H. R. (1992) Differential representation of human skeletal remains in eroded and redeposited coastal deposits: A case study from the Marshall Islands. *International Journal of Anthropology* 7:1–8.

Strobel, B., D. R. Shiveley, and. B. B. Roper (2009) Salmon carcass movements in forest streams. *North American Journal of Fisheries Management* 29:702–714.

Tackett, E. C. and K. Whitfield (1987) *Underwater Crime Scene Investigation: Organizing, Training, and Equipping the Dive Team on a Budget*. Sub-Sea Services, Woodland, WA.

Teather, R. G. (1994) *Encyclopedia of Underwater Investigations*. Best Publishing, Flagstaff, AZ.

Thompson, C. E. L., S. Ball, T. J. U. Thompson, and R. Gowland (2011) The abrasion of modern and archaeological bones by mobile sediments: The importance of transport modes. *Journal of Archaeological Science* 38:784–793.

Thorne, C. R., J. C. Bathurst, and R. D. Hey (1987) *Sediment Transport in Gravel-Bed Rivers*. Wiley, New York.

Trapani, J. (1996) *Hydrodynamic Sorting of Avian Skeletal Remains*. Senior Honors Thesis, State University of New York, Binghamton, NY.

Trapani, J. (1998) Hydrodynamic sorting of avian skeletal remains. *Journal of Archaeological Science* 25(5):477–487.

Valente-Aguiar, M. S., A. C. Falcao, T. Magalhaes, and R. J. Dinis-Oliveira (2020) Cadaveric ichthyofauna of the Madeira River in the Amazon basin: The myth of man-eating piranhas. *Forensic Science, Medicine and Pathology* 16(2):345–351.

Van Daalen, M. A., D. S. de Kat, B. F. Grotebevelsborg, R. D. Leeuwe, J. Warnaar, R. J.Oostra, and W. L. Duijst-Heesters (2017) An aquatic decomposition scoring method to potentially predict the postmortem submersion interval of bodies recovered from the North Sea. *Journal of Forensic Sciences* 62(2):369–373.

Van Orden, E., and A. K. Behrensmeyer (2010) Bone abrasion and transport distance: Taphonomic experiments in the East Fork River, Wyoming. *Journal of Vertebrate Paleontology* 30:181A.

Vanin, S., and S. Zancaner (2011) Post-mortal lesions in freshwater environment. *Forensic Science International* 212:e18–e20. DOI: 10.1016/j.forsciint.2011.05.028.

Varricchio, D., F. Jackson, B. Scherzeer, and J. Shelton (2005) Don't have a cow, man! It's only actualistic taphonomy on the Yellowstone River of Montana. *Journal of Vertebrate Paleontology* 25:126A.

Voorhies, M. R. (1969) Taphonomy and population dynamics of an early Pliocene fauna, Knox County, Nebraska. *University of Wyoming Contributions to Geology, Special Papers* 1:1–69.

Wallace, J. R. (2019) Computer-aided image analysis of crayfish bitemarks—Reinterpreting evidence: A case report. *Forensic Science International* 299:203–207.

Wallace, J. R., R. W. Merritt, R. K. Kimbirauskas, M. E. Benbow, and M. McIntosh (2007) Caddisfly cases assist homicide case: Determining a postmortem submersion interval (PMSI) using aquatic insects. *Proceedings of the American Academy of Forensic Sciences* 13:291–292.

Wallace, J. R., R. W. Merritt, R. Kimbirauskas, M. E. Benbow, and M. McIntosh (2008) Caddisflies assist with homicide case: Determining a postmortem submersion interval using aquatic insects. *Journal of Forensic Sciences* 53(1):219–221.

Weigelt, J. (1989 [1927]) *Recent Vertebrate Carcasses and Their Paleobiological Implications*. Reprint ed., translated by J. Schaefer. University of Chicago Press, Chicago.

Woodruff, D., and D. Varricchio (2008) Modeling an *Oryctodromeus cubicularis* (Dinosauria) burrow. *Journal of Vertebrate Paleontology* 28:162A.

Woodruff, D., and D. Varricchio (2011) Experimental modeling of a possible *Oryctodromeus Cubicularis* (Dinosauria) burrow. *Palaios* 26:140–151.

Yang S. H., X. M. Huang, R. Xia, Y. C. Xu, and T. D. Dahmer (2011) Use of femur bone density to segregate wild from farmed Dybowski's frog (*Rana dybowskii*). *Forensic Science International* 207:61–65.

Yezzi-Woodley, K., M. Tappen, R. Coil, and S. Gogol (2018) Rivers and bones. *Open Rivers: Rethinking Water, Place & Community* 12:37–50.

Young, T. S. (1989) *A Taphonomic and Paleoecological Study of the Late Pleistocene Vertebrate Deposit from the St. Marks River, Wakulla County, Florida*. M.S. Thesis, University of Georgia, Athens, GA.

Marine Environmental Alterations to Bone

7

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Contents

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> Mr. Vaughan, what we are dealing with here is a perfect engine, ahh… an eating machine. It's really a miracle of evolution. All this machine does is swim, and eat, and make little sharks, and that's all.
>
> **—Oceanographer Matt Hooper**
> *Jaws*

Introduction

Coastal areas are a frequent setting for forensic investigations, given the frequency of deaths at sea from homicide, suicide, and accidents (Boyle et al. 1997; Copeland 1987; Ebbesmeyer and Haglund 1994, 2002), burials at sea (London et al. 1997), the use of the ocean for disposal after terrestrial homicide (Ebbesmeyer and Haglund 2002), and the potential for transport of remains from river systems into the ocean (Bassett and Manhein 2002; Brooks and Brooks 1997; Dilen 1984; Haglund and Sorg 2002; Nawrocki et al. 1997; Chapter 6, this volume). Coastal margins present an impenetrable barrier to the further transport of bodies or isolated skeletal elements moved by currents or wave action, with tidal fluctuations allowing objects to be deposited above the water line (Berkeley 2009; Liebig et al. 2003, 2007; Pokines and Higgs 2015; Pyenson 2010; Vullo 2009). Coastal margins also attract large numbers of people into a setting where any remains (skeletonized or fleshed) washing ashore are usually deposited in an exposed area devoid of plant cover. The overall effect is the concentration of many casual observers into a narrow area where exposed remains are typically easier to spot than in other terrestrial settings (forests, grasslands, etc.). The discovery of remains with soft tissue also may be aided by the attraction of avian and terrestrial scavengers feeding in groups. Bodies floating in harbors or other waterways high in marine traffic also increase their chances of discovery, as do suicides or accidental falls from bridges spanning these areas (Ebbesmeyer and Haglund 1994, 2002). This intersection of human activity with the other factors noted increases the frequency of discovery and recovery of human remains from these settings, and the attraction of humans to marine areas with their inherent lethal dangers increases the relative amount of remains recovered from these environments.

This chapter focuses upon the taphonomic alterations typical of skeletal remains recovered from marine environments and how these differ from alterations caused in freshwater or terrestrial environments. Knowledge of these taphonomic alterations is crucial toward understanding the depositional context of the remains as well as distinguishing natural alterations to bone from human sources, including perimortem trauma. Aquatic habitats also offer increased opportunities for biological organisms to colonize remains over terrestrial habitats, creating some taphonomic alterations that are highly distinctive in this regard (Parsons and Brett 1991; Sorg et al. 1997). Transport, decomposition, and scavenging of soft tissue are also examined, as these processes cause taphonomic effects to bones.

Decomposition and Scavenging in Marine Environments

A general pattern has been found across a range of environments that humans and other remains decompose more slowly in water than in terrestrial environments (Anderson 2008; Anderson and Bell 2014; Anderson and Hobischak 2002; Payne 1965; Sorg et al. 1997;

Weigelt 1989 [1927]). This reduced rate of soft tissue loss is a function of multiple factors, including temperature. Perhaps the most important among these is the reduced ability or complete exclusion of fly (dipteran) maggot masses to colonize a floating or sunken body (Westling 2012). A bloated body, floating to the surface remains approximately 80% under water (Dilen 1984), limiting its exposure even when at the surface to colonization by non-marine organisms.

When unscavenged by larger taxa in terrestrial environments, maggot feeding is responsible for the bulk of tissue consumption in a decomposing vertebrate, provided that the temperature and other environmental requirements (including a lack of desiccation of the carcass soft tissue) are met. Additional invertebrate feeding also removes the soft tissue, including beetles of the family Dermestidae, which tend to become more dominant at a set of vertebrate remains after the fly mass has reduced and the remaining soft tissue has become desiccated. Decomposition in water is also inhibited by the generally reduced temperatures, which slow bacterial growth. In addition, aerobic bacterial growth is inhibited by the anoxic conditions sometimes reached, which also may exclude larger scavengers (Anderson and Bell 2014, 2017).

Scavengers also may be partially excluded in cases where bodies are lost in shipwrecks or air crashes and are sealed inside, although a multitude of marine organisms may still reach bodies under these conditions, especially arthropods (De Donno et al. 2014; Foecke et al. 2010; Introna et al. 2013; Raymer 1996). Rapid siltation of portions of wrecks also may exclude macroscavengers, thus leaving behind relatively intact and articulated sets of skeletal remains even hundreds of years later, or highly commingled and incomplete remains where these conditions are not met (Bell and Elkerton 2008; Bell et al. 2009; Stirland 2005).

Notable shipwrecks in this regard include the discovery in 2002 of two largely intact skeletons of crewmembers of the USS *Monitor*, which sank in a storm in 1862. These skeletons were in excellent condition and in articulation and were found under the turret of the ship (Fox 2003). In contrast, despite multiple expeditions with crewed and remote submersibles and its deep, cold water resting place, no human remains from the RMS *Titanic* have been discovered to date. Some possible intact remnants of clothing with apparently no remains contained within have been located (National Oceanic and Atmospheric Administration 2017). Introna et al. (2013) reported on 52 bodies recovered from the wreck of the *Kater Radez I* which were mostly in good condition. Most soft tissue loss was from the (exposed) head/neck region and hands. This ship sank in the Adriatic Sea to a depth of 800 m, where the water temperature remained near 4°C for the seven months prior to recovery. The bodies were protected by the compartmentalization of the ship and the presence of heavy clothing. Importantly, two bodies discovered from outside of the wreck after only four months were skeletonized.

As a further illustration of the great differences in soft tissue preservation that may occur in deep marine environments, Dumser and Türkay (2008) reported the preservational state of remains from two separate air crashes, one west of Namibia in the Atlantic Ocean and the other south of Sicily in the Mediterranean Sea. In both cases, human remains were recovered from a depth of 540–580 m, with a postmortem submergence interval (PMSI) of three months for the Namibian air crash and 34 days for the Sicilian air crash. The former yielded a set of completely skeletonized remains, still loosely associated via their surrounding clothing, while the latter yielded a complete set of remains, still clothed, and with skeletonization only of the skull. While the Namibian remains had a PMSI triple that of the Sicilian remains, Dumser and Türkay (2008) attributed the great difference in soft tissue preservation (and the lack of skeletal disarticulation afforded by it) to the presence of large biomasses of amphipods (tiny arthropods) of the family Lysianassidae or related taxa in the Namibian waters. The Mediterranean waters are depauperate of these highly necrophagous taxa, which in many ways may fill the role of primary soft tissue reduction in marine environments that dipteran maggots play in terrestrial ecosystems. Dumser and Türkay (2008) also noted that the small amounts of soft tissue consumption of the Sicilian bodies likely can be attributed to larger arthropods, order Decapoda (including crabs, lobsters, etc.).

The rate at which small marine vertebrate and invertebrate scavengers can reduce a mammal carcass is highly variable and is dependent on water temperature, presence of other scavenger species, and the depth of the carcass. Jones et al. (1998) observed the rates of carcass consumption of three small cetacean (dolphin and porpoise species *Lagenorhynchus acutus, Phocoena phocoena*, and *Delphinus delphis*) full or partial carcasses placed on the abyssal plain at depths of 4000–4800 m in the northeast Atlantic Ocean. These species are comparable in mass to adult humans. Scavenging loss of tissue was measured over intervals of 36, 152, and 276 h. Even at this great depth, scavenging ensued and proceeded rapidly. The carcasses were monitored remotely, which showed that the carcasses were scavenged rapidly by multiple species of fish and invertebrates. Removal of soft tissue proceeded at rates ranging from 0.05 to 0.4 kg/h. The half-carcass used for the 276 h interval was nearly skeletonized, with only connective tissue still remaining. The main vertebrate scavengers were grenadier fish (*Coryphaenoides armatus*). Primary invertebrate scavengers again were amphipods (at least seven species present), and species of decapod and mollusk (gastropods) were also noted. A turnover of species was noted over time, similar to terrestrial colonization of carcasses by arthropods. Anderson and Bell (2014) recorded several crustacean species scavenging pig (*Sus scrofa*) remains submerged at 99 m in the Saanich Inlet, British Columbia, Canada. Three species (*Munida quadrispina*, *Pandalus platyceros*, and *Metacarcinus magister*) were the most abundant and fed throughout the days/nights, removing the soft tissue and leaving cartilage generally last. Crustacean feeding was aided in one case by a shark bite that breached the skin, which allowed feeding activity to focus there. Some tissue reduction directly by shark also occurred. Skeletonization took as long as 135 days, likely due to anoxic conditions for part of the deposition time for one carcass, and as little as 38 days, including most cartilage, for another. Anderson and Bell (2017), however, found much more rapid skeletonization among pig carcasses in even deeper water (170 m) in the Strait of Georgia, British Columbia. Skeletonization took only 8–24 days, varying by season. The bulk of soft tissue loss, as previous, was through crustacean feeding, including amphipods. Anderson and Bell (2016) found even faster skeletonization of pig carcasses at a depth of 300 m in the Strait of Georgia. Skeletonization was primarily by a dense colony of amphipods and took 3–4 days, with only minor feeding by sharks.

Natural Flotation, Bloating, and Water Pressure

Bodies without flotation devices attached will float or submerge, depending upon the presence of air in the lungs, gases in the intestinal tract, and later the presence of decomposition gases building up internally. The specific gravity (density relative to freshwater) of a human body with these potential gas pockets filled is greater than freshwater (1.000, by definition) or typical seawater (1.026). As a body begins to sink, the increasing pressure of the water (one additional atmosphere per 10 m of depth) on the remaining gas pockets will cause them to compress, further decreasing the body's buoyancy (Donoghue and Minnigerode 1977). The main determinant of whether a body sinks or floats initially is the amount of air remaining in the lungs. Even at residual lung capacity (the amount of air remaining after maximum exhalation), 69% of bodies float in seawater, following the sample of 98 (living, healthy) adult males examined by Donoghue and Minnigerode (1977). In freshwater, with its lower density due to the lower amounts of dissolved minerals, the amount of bodies that floated under these conditions plummeted to 7%. Variations among individuals are caused by multiple factors, including relative lung volume and amount of adipose tissue. The residual lung capacity is roughly equivalent to the amount of air in a recently deceased person's lungs when entering the water, provided that water has not filled the lungs and decreased overall buoyancy. Only minor amounts of additional mass are needed to sink a body, so drowning victims are more likely on average to sink initially. Weighting down by dense objects typically attached to persons in or around water, including tools, fishing gear and nets, heavy footwear, or deliberate weighting for divers to achieve neutral or negative buoyancy, also may interrupt this delicate balance and cause a body to sink.

The multiple atmospheres of pressure exerted by deep water can prevent a decomposing set of remains from ever rising to the surface from the expansion of decomposition gases, even very large taxa such as whales (Allison et al. 1991). The temperatures at great depths are also usually low enough to slow bacterial activity, further delaying decay and the generation of gases. Eventually, an advanced state of decomposition will allow the decay gases to vent, eliminating any further chance of the remains rising to the surface (Allison et al. 1991). The duration that a body decomposing in a marine environment may float is therefore variable and also influenced by prior trauma. Raymer (1996) noted in his personal account of US Navy salvage operations aboard the sunken USS *Arizona* months after the Pearl Harbor attack that several bodies were still floating within the flooded compartments, largely held together by their clothing.

Given individual variation, amounts of trauma and postmortem scavenging (which would allow some decomposition gases to vent), and ocean temperature (varying the amount of bacterial activity), there is no absolute minimum depth beyond which a human body decomposing on the bottom will fail ever to rise to the surface from decompositional bloating. Certainly, for most areas of the open ocean where depths exceed 3 km (the abyssal plain), the amount of water pressure makes it impossible for a sunken body ever to rise to the surface unaided. Most bodies in coastal areas, however, are likely floating in hundreds of meters of water or less. Data also are limited by the lack of experimentation on human bodies. Anderson and Hobischak (2002) decomposed a total of twelve 20–25 kg pigs off the coast of British Columbia, Canada. These pigs were tethered to the bottom at two locations, at depths of 7.6 m and 15.5 m, with tidal variances in the 1.5–3.0 m range. Only head trauma was accrued when the pigs were euthanized. The pigs could not be observed on a continual basis due to the location, but it appears that at least some of the pigs never floated from among the samples at both depths. Anderson (2008) was able to monitor a 26-kg pig carcass remotely in 94 m of ocean water in this same marine area. The temperature at this depth was from 9.5°C to 9.8°C, and the water was poorly oxygenated. This carcass also was tethered to the bottom and did not refloat during the entire length of the experiment (23 days). The water at this depth added over 9 atm above surface pressure, so the carcasses were unlikely ever to float to the surface.

Adipocere Formation

Multiple studies in both freshwater and saltwater environments have noted the formation of adipocere, and otherwise skeletonized remains from these environments may still be associated with this decomposition product adhering. Adipocere forms from the fat tissues of decomposing bodies and is a white/gray/beige soap-like product that can remain friable or become more dried and brittle but resists additional decomposition and can persist for centuries or longer (Schoenen and Schoenen 2013; Chapter 5). As the adipose tissue breaks down, the triglycerides turn into fatty acids aided by the lipases present in the host body, which are subsequently hydrolyzed and hydrogenated. It is known to form through bacterial action under anaerobic conditions. In particular, the presence of the anaerobic bacteria *Clostridium perfringens* and the optimal temperature range of this species (21°C–45°C) facilitate adipocere formation (O'Brien and Kuehner 2007). Adipocere forms under a broad range of environments in both terrestrial and aquatic environments, including freshwater, saltwater, wetlands/bogs, soil burials, coffin burials, and surface deposits (Schoenen and Schoenen 2013; Ubelaker and Zarenko 2011). Its formation is also enhanced by a lack of scavenging; if more fatty tissue remains for breakdown instead of being consumed by macroscavengers (large vertebrates) and microscavengers (amphipods, dipteran larvae, etc.), then the available supply of fatty tissue for conversion to adipocere is much greater. With the majority of its remaining soft tissue converted to adipocere or consisting of less digestible connective tissue, individual carcasses often become far less attractive to subsequent scavengers, and the adipocere may persist even in an exposed setting. Adipocere may continue to adhere to bones, even when recovered disarticulated and largely unprotected from a marine environment (Pokines and Higgs 2015) and may be the only remnants of soft tissue on the exterior. It also may persist within cancellous bone (Figure 7.1) and become exposed from battering and rounding (see "Sediment and Substrate Abrasion" section, below).

Adipocere formation has been detected in a variety of marine contexts, even where this optimal temperature range (21°C–45°C) is not met (as is usually the case in ocean water, especially at depth). Anaerobic conditions and a lack of scavenging can occur in deep marine environments. Adipocere therefore may still form, but slowly. Kahana et al. (1999) examined the remains of 13 crewmembers recovered over the course of 433 days, trapped in the sunken ship *Mineral Dampier* at an approximate depth of 65 m in the East China Sea. These cadavers were recovered over the course of multiple dives to the wreck, after periods of 25, 38, 68, 109, and 433 days, from the same mostly sealed interior environment. Adipocere was detected on the subcutaneous tissue of the cadavers at 38 days from the time of their deaths. The seawater at that depth was 10°C–12°C, below the optimal range for *Clostridium perfringens*. By 68 days, adipocere formation was extensive, and by 109 days, total saponification had occurred, with the formation of a friable crust and complete skeletonization. Other researchers have indicated the presence of adipocere, including Lewis et al. (2004) on the remains recovered from the fishing trawler *Ehime Maru* off the coast of Oahu, USA. Eight sets of largely intact remains were recovered from inside the ship, which initially sank at 610 m and was moved to shallower water (35 m) for the interior recovery. The remains therefore spent the majority of time in a cold water environment, as the water temperature at the initial wreck site was 5°C–6°C, where the ship remained for 8 months, and 25°C at the final site, where recovery began immediately after moving and proceeded for 3 weeks. Six of seven sets of mostly intact remains, with varying degrees of soft tissue preservation, exhibited adipocere formation.

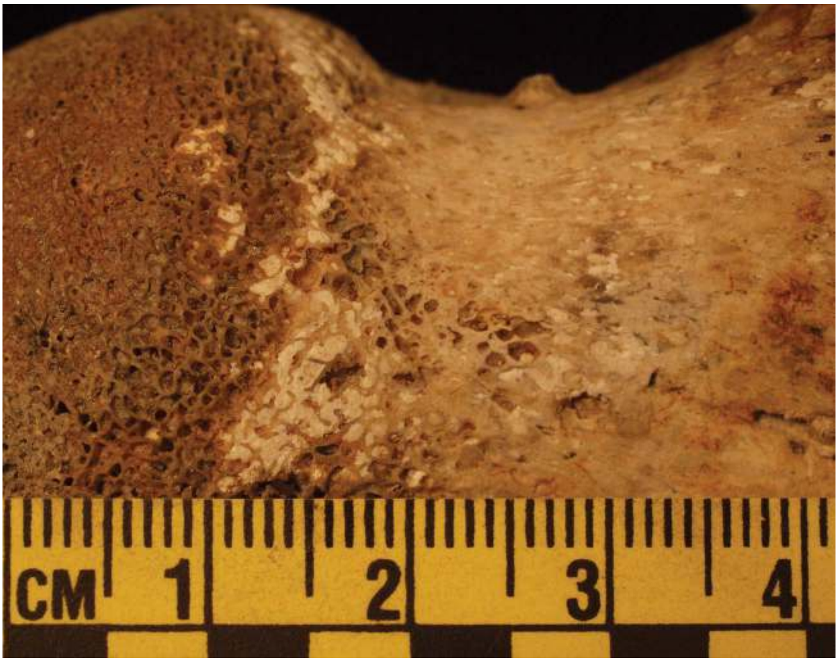

Figure 7.1 Proximal femur from a marine context, Massachusetts, USA. The cancellous bone exposed through abrasion and battering contains small (white) areas of adipocere. The scale is in cm.

Estimation of the Postmortem Submergence Interval (PMSI) from Decomposition Scoring

Due in part to the effects of scavenging of soft tissue noted above, the estimation of the PMSI from decomposition state of bodies encounters similar problems as those in terrestrial environments (Chapters 3 and 9). Bodies in water proceed through stages broadly similar to terrestrial decomposition, but the water environment poses different challenges for scoring and interpreting these stages and can be affected by the flow rate, with the rate of apparent decomposition increasing in faster water due to additional loosening of soft tissue and articulations (Palmer 2020). The stages of decomposition in water have been recorded as: (1) submerged fresh, (2) early floating, (3) floating decay, (4) bloated deterioration, (5) floating remains, and (6) sunken remains. The structure of these stages presupposes that the body does float to the surface due to bloating and other factors, but as indicated above, this is not always the case (Payne and King 1972).

Heaton et al. (2010) examined the records for 187 cases of bodies recovered from waterways in Scotland and England over a 15-year period; 32 cases were found while submerged (sometimes due to being caught on objects), and the rest were floating. Paralleling the work of Megyesi et al. (2005), they devised a scoring scale for three body regions, the face (1–8), torso (1–8), and limbs (1–9), with a score of 1 in each case indicating no visible changes/fresh and a maximum score indicating skeletonization and disarticulation. Intermediate observations include discoloration, wrinkling, and sloughing off of skin. Decomposition was modeled as primarily a function of environmental temperature, calculating Accumulated Degree-Days (ADD) in a centigrade scale but for water temperature instead of air temperature (Megyesi et al. 2005). Heaton et al. (2010) produced a single-regression line equation ($r^2 = 0.77$) and a 95% confidence interval for the total aquatic decomposition score (TADS):

$$\text{TADS} = -3.706 + 7.778 \log_{10} \text{ADD}$$

The formation of adipocere, heavy clothing, and animal scavenging can decrease the accuracy of TADS scoring. In a sample of 68 bodies from sequestered and non-sequestered environments in the Adriatic Sea, De Donno et al. (2014) reported wide variability in the estimation of PMSI. Mateus and Vieira (2014) examined a case with the simultaneous drowning along a shore of six individuals in Portugal and found that bloating leading to floating of bodies occurred in the ADD range of 100–140. The partial surface exposure of these remains could affect subsequent decomposition patterns and scoring differently from non-floating remains in an environment that was otherwise similar.

Van Daalen et al. (2017) examined a sample of 38 cases from the North Sea from 1990 to 2013 and developed an aquatic decomposition scoring system with descriptions and pictorial examples. Their scale also parallels the work of Megyesi et al. (2005) and scores three body regions, the face, body, and limbs, with a score of 1 in each case indicating no visible changes/fresh and a maximum score of 6 score indicating skeletonization. Their scoring, however, does include some sub-stages that allow for multiple decomposition descriptions (marbling, skin slippage/sloughing, hair loss, etc.) and locations within a body region to be assigned the same stage score. No cases with a maximum TADS of 18 were encountered, as these would have been fully skeletonized and therefore unlikely to be recovered in the open ocean. A high correlation was found between TADS and known PMSI for the case sample, although outliers with >500 days PMSI were excluded. Van Daalen et al. (2017) found that TADS predicted 82% of the variation in PMSI.

Marine Transport

The relatively slow decomposition rate in marine environments combined with the action of currents on floating remains can lead to the long-distance transport of bodies, even without attached flotation devices in cases where bloating was sufficient to surface them (see "Natural Flotation, Bloating, and Water Pressure" section, above). Regarding this occurrence, it is noteworthy that remains were recovered scattered over an area hundreds of square miles around where the RMS *Titanic* sank on 15 April 1912. One body was spotted 17 miles north of the sinking site on 1 July that year, with 340 recovered total from the deceased (Eaton and Haas 2011:246–251), most of these within a week of the sinking. It was noted that sea life had already begun to alter the remains, and many were afterward buried at sea, since they were judged too decomposed for the return trip to Halifax, Canada, despite the cold temperatures. The life jackets were constructed primarily of natural materials, so these would eventually decompose, too, and release their remains into the water. Modern life jackets are composed of durable artificial materials that likely would resist falling apart for longer than human remains could persist while decomposing (in temperate or warm waters). Dispersal of bodies with flotation devices attached therefore could take place over hundreds of miles of ocean. Ebbesmeyer and Haglund (2002) described the 1875 sinking of the paddlewheel steamship *Pacific* at the mouth of the Juan de Fuca Strait (dividing Washington state, USA, and British Columbia, Canada), where 250–300 people aboard drowned. Most of the individuals likely were wearing some kind of life preserver. Bodies were recovered ashore and at sea over the course of a month afterward, with drifts as far as 100 miles back into the strait. Only about 6% of the bodies were ever recovered, despite the narrowness of the waterway, amount of ship traffic, and amount of shoreline searching that took place.

The distances traveled by floating bodies can be enormous, depending upon the prevailing currents and lack of landfall to halt progress, and travel can be rapid. Giertsen and Morild (1989) reported the long-distance floating of two separate bodies in the North Sea from Denmark to Norway, with a distance of approximately 500 km. Both bodies were the results of falls from fishing vessels, with one floating for 4–6 months and the other floating for 4–6 weeks. Ebbesmeyer and Haglund (1994) found that a body traveled over 32 km to the location ashore that it was recovered in a maximum of 56.5 h in the Puget Sound (Washington state, USA) after a voluntary plunge from a high bridge. Following the collapse of a bridge in Portugal, Blanco Pampín and López-Abajo Rodríguez (2001) reported that bodies were swept downriver and then transported distances of over 220 km along the Portuguese and Spanish coast, in as little as three days in some cases. In this instance, bodies recovered within five days of the accident showed little signs of decomposition, while those recovered after 20 days showed advanced decomposition.

Dispersal of Body Parts

The decomposition and float patterns of bodies in water lead to the gradual dispersal of individual portions of a body, as these are successively lost (Beardmore et al. 2012; Dodson 1973; Haglund 1993; Stojanowski 2002; Voorhies 1969). As Haglund and Sorg (2002) noted, the typical alignment of a floating human body is very different from that of most other animals. Human arms and legs are very long and large relative to trunk size, and these along with the head tend to dangle inferiorly freely as the body drifts, posterior side up. Due to the relative density of the head, arms, and legs vs. the less dense trunk (which has some gas spaces filled or the body would not be floating at all without artificial help; see "Natural Flotation, Bloating, and Water Pressure" section, above), this position is relatively stable. Advanced bloating of the abdomen may change this relationship and cause a human body to float anterior side up (Haglund and Sorg 2002). Other animals, such as pigs, have limbs that are shorter and smaller relative to their trunks, so their floating position is likely to be much more variable, especially after advanced decomposition begins. This difference in overall body proportions makes pigs, the usual human analog for taphonomic experiments, particularly unsuited to study the effects of human body movement in water, which is in part why multiple experimenters (D'Alonzo et al. 2012; Dilen 1984) have opted to use dummies to mimic natural human drift characteristics. This typical human drift position also allows the extremities to be dragged across shallow bottom surfaces or to become snagged on objects to a greater degree than for many other drifting species, such as seals with their shorter limbs and streamlined bodies.

As decomposition proceeds in water environments, the extremities tend to be lost first (Haglund 1993; Haglund and Sorg 2002). This includes the mandible, which can swing freely in this environment. Haglund (1993) plotted the loss of body parts from 11 sets of human remains from previous investigations in the Seattle and New York City areas, including multiple water settings (still and flowing freshwater and saltwater). He noted that the loss of skeletal parts followed a general sequence: bones of the hands and wrists, being more exposed, were typically lost first. These were followed by the bones of the feet and ankles and then the mandible and cranium. Element loss continued to the lower legs and forearms, followed by the upper arms. This sequence, of course, can be modified by the prior occurrence of perimortem trauma (including boat propeller or marine animal attack), later scavenging, changes in body float position, or elements becoming trapped in clothing. Soft tissue loss occurred most rapidly in areas where it thinly overlays bone, including the skull, hands, and anterior tibia. As bones drop off of a floating body in open ocean, it is very unlikely that these isolated elements will be recovered.

Direct Marine Alterations to Bone

Many data about the taphonomic alterations to bones from marine settings must be derived post hoc, due to the difficulties involved in direct observations of marine feeding behavior even under controlled experimental conditions (Anderson 2008; Anderson and Bell 2014, 2017; Anderson and Hobischak 2002). These difficulties include the specialized equipment and training necessary, such as boats, SCUBA, or underwater monitoring equipment; the physical difficulties of operating in an energetic or deep marine environment; the corrosive saltwater environment; the limited visibility; the necessity in many jurisdictions to acquire permits before depositing decomposing remains in the ocean; and the presence of many macroscavengers that may terminate experiments prior to the observation of slower taphonomic processes.

Sediment and Substrate Abrasion

Marine environments, especially coastal margins, present perhaps the most energetic environment for sedimentary abrasion and rounding of bone, and abrasion also can occur in terrestrial settings from trampling (Madgwick 2014). Freshwater fluvial systems show variable amounts of abrasion to bones that have transported under outdoor experimental conditions, and bones can travel a great distance without necessarily accruing a great deal of abrasion (Aslan and Behrensmeyer 1996; Behrensmeyer 1982, 1988; Chapter 6). This difference may derive from differences in substrate, with marine shorelines being dominated by sand-sized particles of mineral or biological (coral, shell, etc.) origin. Freshwater fluvial systems often are dominated by silt and clay deposits with rounded, rocky beds. Isolated bones in fluvial systems can undergo transport until they are captured by some obstacle and may remain in one place for extended periods. The constant wave action of coastal marine environments tumbles any mobile objects in them through an abrasive substrate, often punctuated with sharp, rocky areas. The overall effect abrades bone to give it a characteristic rounding of edges and loss of extremities (Figures 7.2 and 7.3). Microscopic analysis of abrasion damage can detect directional orientation of striations, thereby indicating the primary direction of water flow (Bromage 1984; Nasti 2017).

Laboratory experiments can only partially mimic the marine environment, since tumbler experiments produce a rotational movement that lacks the mechanics of a marine setting and has a constant amount of force and sediment impact (Shipman and Rose 1988). Irmis and Elliot (2006) attempted to recreate the effects of the repeated sediment abrasion on bone in an experimental setting, using modern shark (*Odontaspis* sp.) and eagle ray (*Myliobatis* sp.) teeth, fine siliceous sand, and saltwater in a reciprocal shaker to simulate

Figure 7.2 Two views of a mandible from a marine context, Massachusetts, USA. Note the overall bleaching, abrasion, and rounding, including loss of most of the rami. Algae is also visible on the teeth. The scale is in cm.

wave action instead of a tumbler. Irmis and Elliot (2006) noted progressive rounding of the crown and root margins and cracking across the crowns. Agitation proceeded in 100 h cycles for a total of 1000 h, at 180 cycles/min. While this degree of abrasion may seem excessive, 1000 h represent less than 42 days in total. Bones recovered from marine coastal margins may have been agitated in the natural environment for much longer, although they likely go through periods of temporary burial in the sand alternating with periods

Figure 7.3 Tibia shaft from a marine context, Massachusetts, USA, showing bleaching and heavy battering, causing pock marking of the surface. The scale is in cm.

of constant wave action (though at a slower rate than 180 cycles/min). Bones in a natural setting are also likely exposed to coarser sand and gravels than in some experimental settings. Other researchers have employed flumes of circulating water and noted that particle size, sphericity, and water velocity as well as bone preservation state (fresh, archaeological, weathered, or fossilized) can affect abrasion results (DeBattista et al. 2013; García-Morato et al. 2019; Griffith 2017; Griffith et al. 2016; Thompson et al. 2013). Researchers also have found in some cases minimal abrasion after extensive experimental tumbling (Argast et al. 1987).

Rounding experiments by Fernández-Jalvo and Andrews (2003, 2016) examined a variety of large mammal bone types (fresh, lightly weathered/dry, highly weathered, and fossilized) in multiple abrasive (very coarse sand, coarse sand, fine sand and silt, and silt and clay) settings. Only previously unabraded bone fragments were used. The bones were agitated in a series of rock tumblers under a constant speed of 15 cm/s, yielding a movement of the bones relative to the sediment of 540 m/h. Experimental periods ran for 72 h, 192 h, and 360 h. Overall, coarser sediments produced greater degrees of rounding on fresh and lightly weathered/dry bone, but this relationship was reversed on highly weathered and fossilized bone. Fresh bones introduced into a marine coastal environment, with their typically coarse sediments, can undergo high amounts of polishing from natural wave agitation. It is also noteworthy that sediment abrasion polishing of bone surfaces can remove earlier signs of weathering, indicating that highly reworked bones recovered from marine coastal environments may no longer have traces of prior deposition on land. Deep cracks from previous advanced weathering in a terrestrial environment, however, may be retained even after substantial abrasion (Fernández-Jalvo and Andrews 2003, 2016). Flume and tumbler experimentation also has indicated that marine abrasion can obscure prior sharp force trauma (Appleton and O'Brien 2015) or other previous damage including tooth marks (Gümrükçü 2017; Gümrükçü and Pante 2018; Shipman and Rose 1988).

Bones also may get dragged by wave action over jagged rocky outcrops and other sharp objects, which can leave deeper traces of abrasion behind, provided that further polishing does not remove these traces. This type of surface scoring can be oriented in any direction, although multiple scores often will be created in parallel as the bone is dragged across an object with multiple projections. This type of surface scoring is analogous to that caused by tramping of bone in terrestrial settings, where the bone is pushed against surface rocks or against those adjacent to it in the soil.

Sediment Embedding

Osseous remains recovered from coastal settings frequently have embedded sand particles in their exposed medullary cavities, trabecular bone, foramina, and surface cracks (Irmis and Elliot 2006). During initial recovery, transport, processing, storage, and analysis, it is important to retain this evidence of the specimen's origin, since sand particles adhere less strongly to bone than do terrestrial sediments heavy in clay and organic content. This simple but effective source of contextual evidence therefore can be lost readily or is frequently not recorded in forensic taphonomic examinations.

Concretion

Concretion is the deposition of a cement-like substance around ferrous objects in saltwater (Green 2004:262), which can encompass any adjacent object, including bone. This form of taphonomic alteration is more relevant to underwater archaeological excavations than to forensic recoveries due to the time needed for this process to accrue. The presence of concretion on bone therefore may be a useful indicator that bone is of historical/archaeological age instead of recent.

Bleaching and Staining

Bones recovered from marine environments typically become bleached white (Figure 7.2) from chemical reactions with the saltwater. Little is understood about the timing of this change, likely due to the difficulties of recovering experimentally placed bones at known intervals from saltwater settings without significant recovery loss and the amount of time necessary likely exceeding that of available research programs. Data from known forensic contexts regarding this timing is presented in the "Estimation of the PMSI from Bone Changes" section, below.

Marine bleaching can be distinguished from the bleaching caused by sunlight in the subaerial weathering of bone (Chapter 11) by its overall pattern, which typically affects all areas of a bone simultaneously and is unsurprising, given the saltwater environment. Subaerial weathering often advances to greater degrees on the portion of a bone most exposed to sunlight, while the downward-facing aspect of the bone lags multiple weathering stages behind. Bleaching caused by subaerial weathering is also accompanied by cracking and exfoliation of the bone surface, which is not typically the case for marine-bleached bone. Bones washed ashore after having undergone marine bleaching are often in an exposed location and can start to proceed through the subaerial weathering stages that are typical to terrestrial surface deposits. Thus, bones received from coastal margins can have both types of bleaching. Salt crystal formation from drying bone (see "Salt Crystal Formation" section, below) also may mimic the more common cracking caused by subaerial weathering. Some marine settings also cause the mineral staining of bone (Chapter 12).

Surface stains are also common on marine bone and are often ascribable to mineral deposition. Reddish coloration is likely due to some combination of iron oxides (Figures 7.4

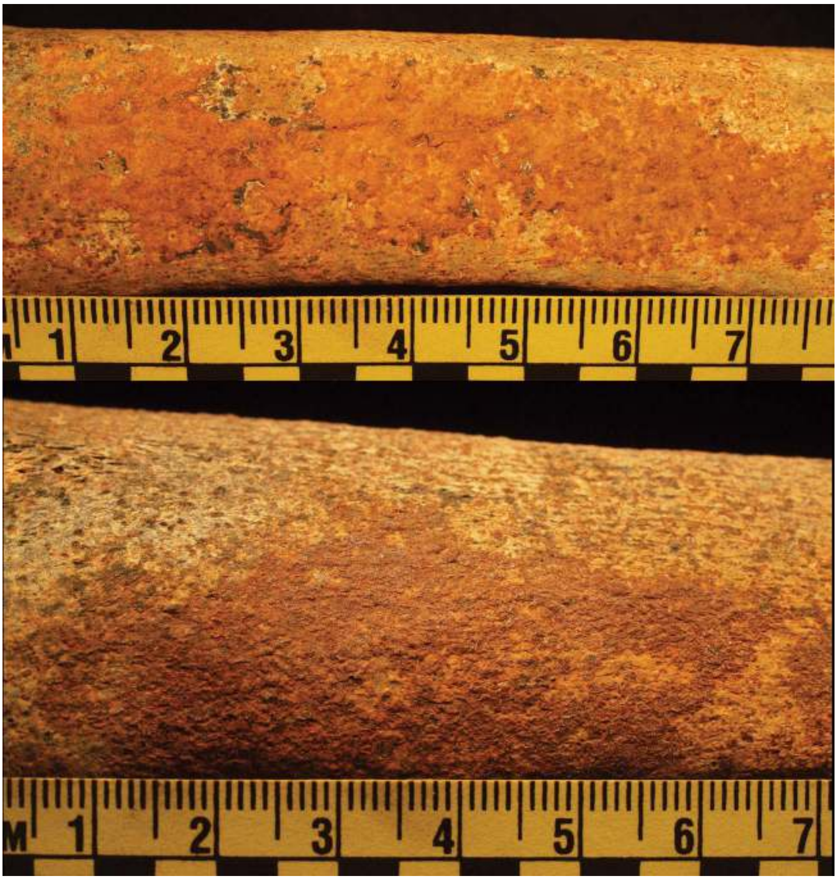

Figure 7.4 Tibia shafts from marine contexts, Massachusetts, USA, showing heavy amounts of and variable shades of red mineral staining likely resulting from iron oxides. The scales are in cm.

and 7.5), with dark colors likely due to the presence of iron sulphides, formed under anaerobic conditions (Higgs et al. 2011b; Pokines and Higgs 2015) (Figure 7.6). Areas of mineral staining can get worn away by subsequent surface rounding, and mixed patches of red and dark ("calico") staining often occur. Dark organic staining (Figure 7.7) that appears to be emerging from within the bone also has been noted on sea mammals including seals (Phocidae), which have a high fat content and continue to exude grease for some time. This dark staining appears to form from the decomposition of the fat content and is usually accompanied by odor. The authors have not noted similarly dark staining on human bones, even though these can continue to exude grease, giving a yellow staining usually to the epiphyses of long bones from marine environments (Figure 7.8).

Salt Crystal Formation

Bones submerged in saltwater for extended periods absorb salt ions (primarily Na^+ and Cl^-) into their porous structure. This porosity is increased by the breakdown of the organic collagen component and the partial dissolution of the mineral portion, expanding extant pores and channels. When the bone is dried, the salt can recrystallize, with

Figure 7.5 Cranium from a marine context, Massachusetts, USA, showing more diffuse red mineral staining likely resulting from iron oxides.

Figure 7.6 Proximal femur from a marine context, Massachusetts, USA, showing dark mineral staining likely resulting from iron sulphides. Subsequent abrasion has worn away some of the mineral staining. The scale is in cm.

Figure 7.7 Distal tibio-fibulae of Phocidae, marine contexts, Massachusetts, USA, showing (left) brown staining from decomposing internal fat leaching out of the bone and (right) dark staining that may derive from additional decomposition of internal fat content. The scale is in cm.

the crystal expansion causing cracking and surface flaking of the bone (see Figure 12.15, Chapter 12, this volume). Skeletal remains that have been submerged long-term in the ocean must be flushed with freshwater in order to reduce the salt content. Following the guidelines put forth by Hamilton (1997, 1999/2001, 2010), the recommended conservator process is to keep the bone in 100% saltwater until ready for processing. It is then placed into successive dilutions of saltwater to freshwater: 75% saltwater/25% freshwater; 50% saltwater/50% freshwater; 25% saltwater/75% freshwater; and then 100% freshwater. The bone is then passed through successive rinses of freshwater or through running freshwater until the soluble salt level reaches that of the local freshwater. Distilled water then replaces the freshwater until the soluble salts are removed or reach minimal levels, as determined by an electrical conductivity meter. The bone can then be slowly air-dried at this time.

Figure 7.8 Proximal tibia, marine context, Massachusetts, USA, showing bleaching and yellow staining from fat leaching out of the epiphysis. The scale is in cm.

Human skeletal remains washed ashore and recovered some time later are likely to have dried out and begun salt crystallization. This process can be highly damaging to the bone (Prassack 2011) and is already unavoidable under these circumstances.

Adhering Marine Taxa

Multiple marine taxa adhere themselves to hard substrates, either for support (sessile life forms) or to feed upon organisms already colonizing that substrate, such as limpets (a common gastropod) feeding upon algae. The buildup of these colonizing organisms on artificial surfaces, such as ships' hulls and propellers, is termed *biofouling* (Bixler and Bhushan 2012). This term also may be extended to natural inorganic particulate buildup. When these taxa adhere themselves to bone, either the attaching organisms themselves or traces of their attachment method may be preserved on the surface and indicate deposition in a saltwater (or at least an aquatic) environment. Many of these taxa disperse via a tiny larval stage, so that the adult forms may grow and develop seemingly spontaneously. These species are very common in the intertidal and shallow marine zones and are frequently encountered or in many cases harvested commercially.

Algae and Kelp

Algae are a diverse and disparate group of marine organisms that range in size from microscopic protists to large seaweeds and kelp. They are found throughout the world in almost every environment. Marine macroalgae or "seaweeds" will be considered here in terms of bioerosion, although microalgae may play a role in the bioerosion of skeletal matter in the marine environment. The classification and evolutionary relationships of algae are a matter of current research, but it has become increasingly clear that the

Figure 7.9 Cranium, marine context, Massachusetts, USA, showing bleaching and area of diffuse green algae staining.

algae are not a taxonomically coherent group of organisms and belong to at least four different kingdoms. The seaweeds have been traditionally divided into three groups: the green algae (Chlorophyceae), the brown algae (Phaeophyceae), and the red algae (Rhodophyceae). This classification is useful for the non-expert and forms the basis for an excellent color guide to the common macroalgae of the world's oceans by Braune and Guiry (2011). Almost all species of brown algae and most species of red algae occur in the marine realm, but a significant proportion of green algae also occur in brackish and freshwater environments.

Algae will colonize almost any hard substrate, including shells and bone as long as they are reasonably stable (Zimmerman and Wallace 2008). Microalgae, as in moist terrestrial environments, can form on marine bones, leaving diffuse green staining (Figure 7.9). Most produce their own food through photosynthesis, so they are restricted

Figure 7.10 Cranium, marine context, Massachusetts, USA, showing bleaching, battering and rounding of structures, and filamentous algae adhering to the temporal. The scale is in cm.

to the euphotic zone (i.e., near the surface and receiving sunlight), which will vary in depth depending on the turbidity of the local seas. Growth rates can vary and are affected by seasonality, as well as a host of other factors such as wave exposure, nutrient availability, and temperature.

The simplest forms of macroalgae are made up of thin filaments (Figure 7.10) that can be branching or unbranching, which can form dense mats that proliferate rapidly to cover their substrate. Larger forms of algae have a more complex three-dimensional structure, termed the thallus. This can be divided into various regions such as leafy fronds or lamina. In some forms such as kelp, there is a stem-like structure called the stipe, which is attached to the substrate by a holdfast. Holdfasts may be simple disk shapes or have ramulose appendages called haptera that embed the thallus to the substrate. The holdfasts attach to their substrate using a glycoprotein or acid-polysaccharide/protein complex that is strong enough to create a distinct holdfast scar if the algae are ripped away by waves (Bromley and Heinberg 2006). In addition, the algae may leave etching traces on the bone surface. It may be possible to use holdfast diameter to gain an approximation of PMSI, but the relationship between age and holdfast diameter is strongly influenced by wave exposure. The diversity of algal colonization also has been used to estimate PMSI in brackish water (Zimmerman and Wallace 2008), and similar PMSI estimation has been attempted using bacterial colonization in marine water (Dickson and Poulter 2010). Interestingly, algal growth may be responsible for transporting skeletal elements when the buoyancy of attached algae overcomes the mass of the bone (e.g., Gilbert 1984).

In contrast to the more ornate forms taken on by seaweeds, several families of red algae form calcified crusts on their substrate. These are known as the crustose coralline algae (CCA) and are some of the most common algal forms found throughout the oceans (Steneck 1986). Coralline algae vary from flat simple crusts to complex three-dimensionally branching structures known as rhodoliths. The calcareous structures produced by CCA do record growth increments, but their slow growth rates mean that they are probably of more use to archaeological studies. In general, the flat thin forms grow faster than thicker forms. Branching forms typically grow at 0.3–10 mm per year (Steneck 1986).

Figure 7.11 Bones from marine contexts, Massachusetts, USA, showing adhering bryozoan colonies; (top) fibula and (bottom) mandible. The scales are in cm.

Bryozoa

Bryozoa (literally: moss animals) are colonial filter-feeding animals found in both freshwater and marine environments. Colonies (Figure 7.11) are made up of minute (~0.5 mm) individual zooids, housed in a protective covering that may be organic or mineralized (e.g., calcium carbonate), and which may survive long after the animal has died. These zooid colonies can grow into extensive arborescent or foliose forms, but more commonly, they form mats that spread over the surface of a firm substrate. Sorg et al. (1997) suggested that bryozoans might be useful in a forensic context, since the size of the mat colony may be used to indicate a minimum PMSI; however, their variable growth rates mean that this can only be an approximation at best. Their presence on human bones from shipwrecks suggests that there may be some forensic utility warranting further investigation (Steptoe and Wood 2002).

Figure 7.12 Tibia and fibula from the same marine context, Massachusetts, USA, showing adhering dense colonies of acorn barnacles. The scales are in cm.

Barnacles

Barnacles (infraclass: Cirripedia) are members of the Arthropoda Subphylum Crustacea, which includes crabs, shrimp, and lobster. These taxa have a long history of biological study, including early research by Charles Darwin (Love 2002). When in a larval stage, they drift in marine waters until reaching a stable surface on which to grow and remain sessile for their adult lives. They are found in deep water but most abundantly in shallow water and the intertidal zone and only in marine and brackish environments, so their growth on an object indicates its at least temporary deposition in an oceanic setting. They normally grow on rocks but are also commonly found on other biological organisms, including whales, mollusk shells, turtle shells, upon each other, and bone (Figure 7.12). They also grow on artificial objects, including ships' hulls, wooden pilings, driftwood, rope, anchor cables, breakwaters, or any solid object tossed into the ocean. Their removal is a constant requirement of maritime maintenance (Bixler and Bhushan 2012; Dickinson et al. 2009). Acorn barnacles (order Sessilia) are attached directly to substrates and have a rounded shape (Figure 7.13), while stalked or gooseneck barnacles (order Pedunculata) attach by means of a flexible stalk. Their bodies are protected by calcified plates, and these hard parts commonly are preserved after the barnacle dies and the soft tissue decomposes or desiccates (Figure 7.14). Due to their structure and direct attachment to substrates,

Figure 7.13 Cranium, marine context, Massachusetts, USA, showing an adhering dense colony of acorn barnacles. Some barnacles have fallen off, showing barnacle scars, which still allow species identification in this case.

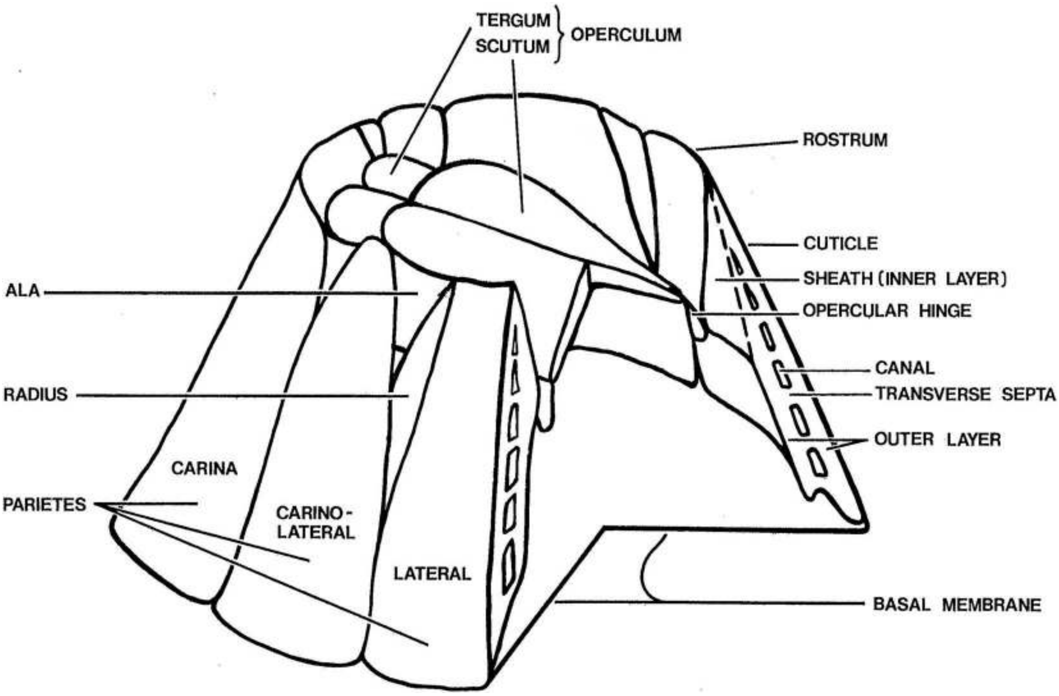

Figure 7.14 Anatomy of an acorn barnacle's skeleton. (Slightly modified from Bourget 1980:489; used with permission, Springer Science + Business Media.)

Figure 7.15 Close up of barnacle scars, tibia from a marine context, Massachusetts, USA. The species is most consistent with bay barnacles (*Amphibalanus improvisus*).

acorn barnacles are more likely to remain adhered to a bone or other objects after it has been deposited on land.

Acorn barnacles attach themselves by their dorsal surface to a hard substrate, and most species capture plankton and other microscopic food by fanning their appendages. Their adhesive is also a natural protein polymer that holds them tightly even to moving objects (marine mammals and ships' hulls) and rocks subjected to heavy wave action (Dickinson et al. 2009; Stewart et al. 2011). The adhering material that is left behind on a bone is termed a *barnacle scar* (Figures 7.13 and 7.15); this material also acts to protect the bone, so areas around barnacle scars may show signs of abrasion and battering to a higher degree. In addition, in some contexts the species of barnacle can be determined from adhering traces of the scar alone. Barnacles are sessile organisms, and indicators of their growth may provide a useful means of determining a minimum value for PMSI. Barnacle growth is recorded in their calcareous plates as incremental growth bands (Bourget and Crisp 1975). Several types of skeletal increments have been recorded in barnacle hard parts: (1) growth bands seen in radial thin sections of the parietes (wall plates), (2) ridges on the external surfaces of the parietes, (3) prominent ridges on the operculum (plates surrounding the aperture), and (4) circular increments of the base plate (Clare et al. 1994; Crisp and Bourget 1985). These increments are influenced by numerous cyclical factors, both internal and external, ranging in their temporal scale from tidal to annual (Crisp and Bourget 1985).

Growth bands seen in radial sections of barnacle wall plates appear to represent cycles of feeding (rapid growth) and stress (reduced growth) that are dominated by the tidal regime of their surroundings. Consequently, barnacles from the intertidal zone, which are subject to tidal cycles of submergence and exposure, show the most defined bands, while those that are continuously submerged (i.e., grow underwater) show less-defined banding. Laboratory experiments have shown that the number of bands corresponds directly to tidal cycles of submergence and emergence, even when the period is artificially manipulated

(Bourget and Crisp 1975). Barnacles grown under uniform conditions in the laboratory, continuously submerged, produce two growth bands per day, presumably because of endogenous rhythms (Bourget 1980). Seasonal variations in the thickness of the growth bands have been recorded where thin bands represent periods of reduced growth in the winter and so may provide a means of aging specimens that are several years old.

Growth ridges on the surface of the plates have received less attention than cross-sectional growth banding, but studies to date show that the two types of growth increment are asynchronous and probably have different underlying causes (Bourget and Crisp 1975). The major ridges (also called hirsute ridges by some authors) on the parietes and opercular plates (see above) can be considered together, since they seem to increase synchronously (Clare et al. 1994). These ridges are the result of the animal's molting cycle but are not always laid down on every molt and would seem to be of little use in aging individuals. Nevertheless, the number of external ridges on the opercula of *Balanus amphitrite* showed a linear relationship with the age of the barnacle over the first 25 days of measurement (Clare et al. 1994). In this instance, each ridge represented 1.3–1.8 days of growth, but the authors noted that in another species, *B. improvisus*, each ridge took 1.8–2.3 days to form, so caution must be exercised when considering this method of aging. In regions of extreme seasonality, "winter rings" may be observed on the outer surface of parietes as distinct overhangs or notches, where growth has severely reduced during the winter (Bourget 1980). These seasonal growth rings offer a means to age animals in the longer term and have been used to age animals on several occasions (Crisp 1954; Bourget 1980).

The fourth type of growth increment, growth rings found on the basal plate, has received almost no attention, but is likely to be the most useful to forensic investigators because of its durability on the attachment surface (Bytheway and Pustilnik 2013). In the absence of data on the periodicity of growth ring formation on the base plate, the total size of the base plate can be considered as an indicator of time since colonization and possibly used to determine a minimum PMSI. The diameter of the base plate increases linearly during the early phases of growth but decreases after maturity. By dividing the total diameter of the base plate by the maximum recorded growth rate, it is possible to obtain a very conservative estimate of PMSI. This method should be used only as a last resort, since growth varies markedly depending on a host of factors. For example, recorded growth rates for the basal diameter of *Balanus balanoides* vary between 33 and 169 μm per day, as do growth rates for a variety of other species (Crisp and Bourget 1985:212–214). Growth rates should be considered on a species-by-species basis, since large species grow more slowly, as do those growing at high tide levels.

Barnacle growth increments have rarely been utilized in forensic cases but are not without precedent. The use of barnacles to estimate the time of immersion for a cadaver recovered from the sea was reported well over a century ago, showing that "in certain cases, zoology can aid forensic science" (Mégnin 1894:110). Two more recent cases where the basal diameter of barnacles was used to provide a minimum estimate of time since death were reported by Sorg et al. (1997) and Skinner et al. (1988). The analysis of growth increments or ridges on barnacle plates was attempted by Dennison et al. (2004) to estimate a minimum time since death, although little methodological information was provided. Some barnacle species also have an annual reproductive cycle and only colonize surfaces to begin their sessile adult phase during certain windows, which must be taken into consideration when estimating the PMSI (Bytheway and Pustilnik 2013).

Mollusks

Members of Phylum Mollusca, Class Bivalvia (i.e., bivalves), include those mollusk species having two shells joined by a hinge, such as mussels, clams, oysters, and scallops. Many of these species are sessile and attach themselves permanently to hard substrates in marine (and freshwater) environments. From there, they filter-feed from the environment. Dispersal is achieved through larval drift, until the larvae attach themselves to a solid substrate and begin to grow. Attachment of mussels (including the commonly consumed marine mussels of the family Mytilidae) to their substrate is achieved with byssal threads known commonly as the "beard" strands. This natural adhesive is formed from secreted cross-linked proteins (Hight and Wilker 2007; Waite 2002). The byssal threads are silk-like and very strong, having to hold mussels firmly attached in the energetic intertidal zone. Byssal threads may still be attached to a bone or other object after the mussel has been detached. Other bivalves, including some clams and freshwater mussels, also attach themselves to substrates using byssal threads, so the presence of these can be used only as an indicator of bone deposition in an aquatic, not necessarily marine, environment. If the bivalve shells are still attached to a bone, their growth bands may be used to estimate PMSI based on known growth rates (e.g., Evans 1968).

Members of Phylum Mollusca, Class Gastropoda, include some mollusk species having just a single, spiral shell (snails) or no shell (slugs). Common marine snails include Littorinidae, the winkles and periwinkles. Limpets (Patellogastropoda) are a ubiquitous taxon of marine snails having a conical, instead of a spiral, shell. Both of these groups are commonly found in the intertidal zone, attached to rocks and other hard surfaces (Figure 7.16). These species are not entirely sessile and can move about on these surfaces when feeding. When needed, including when exposed to the air during low tide, these species adhere tightly to the surface and are difficult to pry loose. Attachment is aided by the secretion of an adhesive mucus (Smith 2002). Their resting spots may also leave an identifiable patch on the substrate, termed a *mollusk homing scar* (Figure 7.17). These often present as a central flat spot that has been protected from other marine taphonomic agencies by the mollusk, with sometimes a surrounding groove worn by the mollusk shell margin. Some species, including slipper shells (*Crepidula* spp.) also leave behind shell

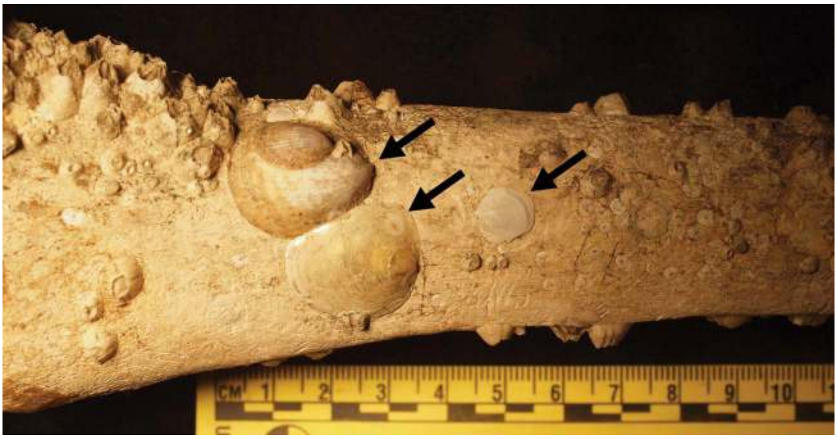

Figure 7.16 Proximal tibia shaft from a marine context, Massachusetts, USA, showing colonization by multiple, small acorn barnacles and mollusks (arrows). The scale is in cm.

Figure 7.17 Examples of mollusk homing scars from marine contexts, Massachusetts, USA. The adhering material has protected the bone, which in adjacent areas shows the effects of abrasion and battering. (Top) endocranial surface crowded with mollusk homing scars likely left by multiple individuals of slipper shells (*Crepidula* spp.) leaving behind shell material; (middle and bottom) femur shafts with mollusk homing scars with central rounded areas surrounded by troughs worn into the bone by the shell margins. The scales are in cm. (Bottom image from Pokines and Higgs 2015:968; used with permission, *Journal of Forensic Identification*.)

material deposited in the central area to allow greater adhesion (Figure 7.17, top). When removed from the ocean while still attached to a bone or other object, a mollusk will eventually dehydrate and die and may remain attached or fall off. Their presence therefore may indicate marine deposition, although their attachment will not be as permanent as some other taxa, including barnacles.

Coral

Corals (Phylum Cnidaria, Class Anthozoa, which also includes anemones) are an abundant, diverse group of sessile marine life forms found throughout the world. Their fertilized eggs drift until reaching a hard substrate, where they attach and begin to grow into their adult polyp form. Some of these (the stony corals or order Scleractinia) form coral reefs through the gradual deposition of calcium carbonate ($CaCO_3$) to house these colonial organisms and act as an exoskeleton. Many of these hard coral species are also symbiotic with forms of algae and therefore are found only in the euphotic zone. Hard corals and reef formation are most common in shallow tropical waters. Substrates for coral formation include rock, dead coral, artificial objects, and potentially bone.

The rates at which coral species can begin to deposit $CaCO_3$ in an identifiable manner is variable and affected by environmental conditions (Bessat and Buigues 2001; Lough and Cooper 2011; Rasher et al. 2012). Deposition of $CaCO_3$ has been measured (linearly) in terms of a few millimeters per year. The annual banding of coral (Lough and Cooper 2011) has potential as a dating source to provide a minimum age of deposition.

Marine Bioerosion

Recent human remains deposited into the ocean are subjected to alteration by taxa that have evolved for millions of years to exploit these large packages of nutrients (bone) in an otherwise nutrient-poor environment (Belaústegui et al. 2012 and references therein; Britton and Morton 1994; Jones et al. 1998). *Bioerosion* is the removal of bone by living organisms, as a result of tunneling into the bone for shelter or nutrition or through marking the surface in conjunction with feeding on attached soft tissues or other adhering organisms. The study of bone bioerosion in marine contexts has been limited to date, and most of the available information has been gleaned from studies of marine mammal remains and paleontological evidence of bone bioerosion.

Human anatomy differs from that of marine vertebrates in multiple relevant aspects, so some types of taphonomic effects that are recorded on the bones of other species are far less likely to occur on human bones. The size of humans is at the lower end of the scale when compared to extant marine mammals, the largest of which (whales) include the largest vertebrate species ever to evolve on the planet. Whale bone has a very high lipid content that serves as an abundant, long-lasting nutrient supply to the organisms colonizing a whale carcass on the ocean floor (Allison et al. 1991; Higgs et al. 2011a). Manatee (*Trichechus* spp.) long bones and ribs have a very high density due to increased mineralization and a reduction of interior spaces (pachyostosis), likely an adaptation to help maintain neutral buoyancy (Clifton et al. 2008). Other differences include reduction or absence of rear appendages of some sea mammals, making their skeletons not easily analogous to humans even where there is a general body size overlap. Deep layers of subcutaneous fat also may alter patterns of decomposition between humans and sea mammals, making skeletonization follow different paths (Higgs et al. 2011a) and expose bones to bioerosion at different times.

Differences in taphonomic alterations between humans and marine vertebrates also may relate to the normal depth range inhabited by the taxon causing the alteration. While human remains may reach that depth as a result of shipwreck or air crash, they are unlikely to be recovered from it as they are from shallower coastal contexts. Newer technology and methods, however, are allowing the recovery of human remains from depths over 500 m (Dumser and Türkay 2008; Lewis et al. 2004). In a more extreme case, several sets of remains were recovered two years later from the June 2009 crash of Air France Flight 447 in the South Atlantic off the coast of Brazil (BEA 2011). The depth of this Airbus A330-203 wreckage ranged up to 4000 m (the abyssal plain), and the recovery of bodies and key pieces of wreckage was through the use of remote submersibles (BEA 2011; Clifford 2011; Purcell et al. 2011). Deep-water dwelling taxa that alter human remains therefore will become more important to forensic analyses as recoveries of this type from ships and aircraft become common, and the taphonomic effects accrued in these environments may differ from what are known to occur to nonhuman species.

Belaústegui et al. (2012) in their review of vertebrate remains in marine settings list microbioerosion (i.e., microboring) and five categories of macrobioerosion: (1) invertebrate grazing traces, (2) osteophagous crab traces, (3) worm borings, (4) bivalve borings, and (5) vertebrate predator/scavenger traces. In addition, Higgs et al. (2012) highlighted evidence of sponge borings in bone as another source of bioerosion. The categories that have the highest relevance to forensic, as opposed to paleontological or marine biological analyses, are discussed below.

Microboring

Marine microboring into bone is caused by microscopic organisms, including fungi, bacteria, and cyanobacteria (Arnaud et al. 1978; Ascenzi and Silvestrini 1984; Davis 1997; Yoshino et al. 1991). These taphonomic alterations (focal destruction) are also evident in bones from terrestrial settings and are discussed in more detail in Chapter 2 of this volume. Evidence from the few available studies indicates that there is a contrast in microboring morphology between terrestrial and marine environments. Wedl-type tunneling is the most common type of focal destruction observed in bone from marine environments (Bell and Elkerton 2008; Trueman and Martill 2002; Yoshino et al. 1991), whereas bacterial focal destruction is more common in terrestrial settings. It is generally thought that Wedl tunneling is caused by cyanobacteria (Bell and Elkerton 2008; Davis 1997) or fungi (Trueman and Martill 2002). The onset of bioerosion may be rapid: Davis (1997) reports that experimentally deployed bones were bioeroded within four days off the coast of Florida, USA.

Microorganisms play key roles in bone bioerosion by enabling and encouraging larger animals to graze the bones. Firstly, the nutritive value of the microorganisms attracts larger animals to graze the surface layers. The bone mineral-collagen matrix is a highly refractile, indigestible food source, but the microbial bioeroders are able to unlock collagen nutrients and make them available to larger animals in the food chain. Secondly, the degree to which the microorganisms penetrate the bone severely compromises its structural integrity, allowing grazers easily to erode the bone.

Invertebrate Grazing Traces

A wide variety of invertebrates are known to graze hard substrates for the microorganisms and algae growing in or on them, including several chitons and gastropod mollusks,

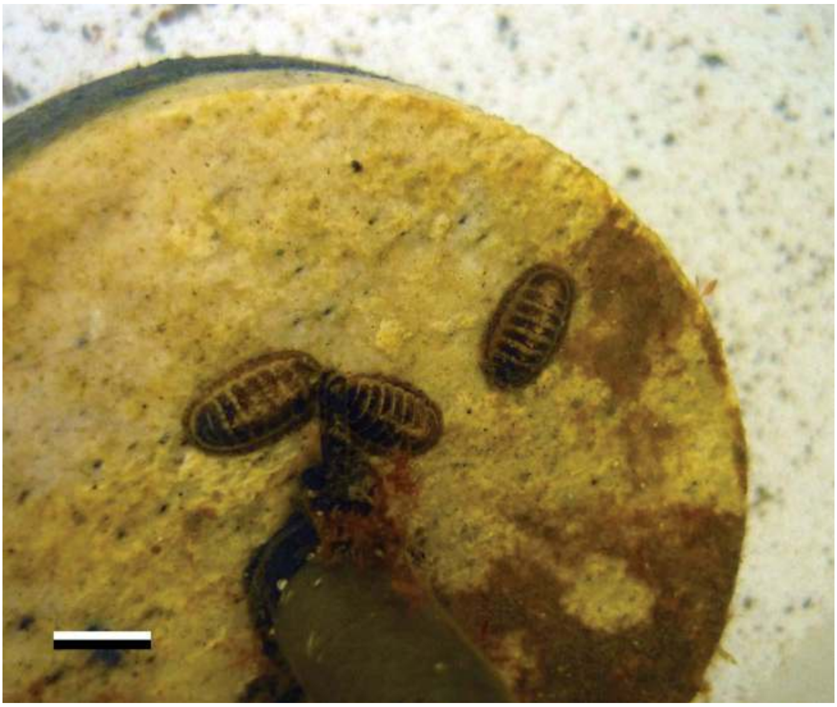

Figure 7.18 Chitons (class Polyplacophora) grazing a sample of whale bone. Note the dark algal growth on the bone's surface (lower right), which has been grazed off the rest of the bone. The surface also shows slight pitting from the grazing action of the chitons. The scale is 1 cm.

sea urchins, and crabs. Representatives from all of these groups have been identified grazing on bones in the marine environment and leave telltale evidence of grazing activity on the bone's surface. Mollusks have a chitinous feeding appendage called the radula that is studded with rows of minute teeth, often hardened by the incorporation of metal compounds. They use the radula to scrape away or rasp algae that are embedded in the bone, thereby removing layers of bone as they do so (Figure 7.18). Radular grazing traces (known as *radulichnus*) consist of parallel striations having a surface relief of 20–100 μm (Bromley 1994). They occur in multiple blocks of parallel striations and may cover a large surface area. Several families of deep-water gastropods are known to specialize on bone and have been found with guts full of bone debris (e.g., Haszprunar 1988; Marshall 1987; Warén 2011). Large deep-sea snails of the genus *Rubyspira* were found feeding on whale bones at a depth of 2890 m in the Monterey Canyon off California, USA, but have not been found on other skeletons shallower than 1500 m in the canyon (Johnson et al. 2010). Bones deposited in shallow waters also may become rapidly colonized by grazing mollusks.

Sea urchins have a five-toothed jaw apparatus that they use to scrape the surface of bones, producing a star-shaped pattern of grooves in the surface. In the paleontological literature, these traces have been given the name *gnathichnus pentax* and are highly distinctive. They indicate marine deposition but offer little information on minimum submergence interval and occur in both deep and shallow settings. Figure 7.19 shows experimentally deployed whale bones being grazed by pencil urchins (Cidaridae) in deep waters off of Scotland.

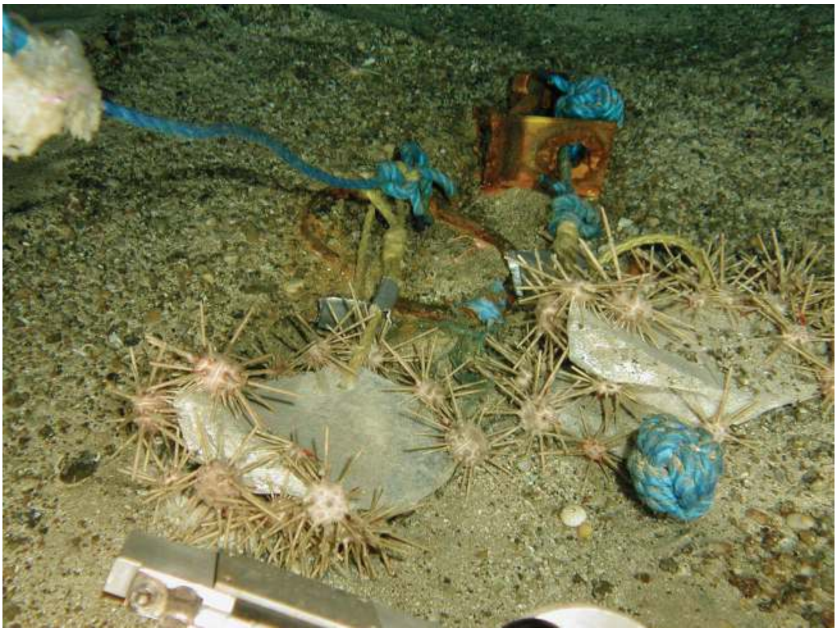

Figure 7.19 Cidarid (pencil) sea urchins grazing on whale bones on the deep seabed.

Osteophagous Crab Traces

Grazing crabs have been documented on bones from deep-water environments. Squat lobsters are frequently observed on whale skeletons on the deep seabed (Lundsten et al. 2010; Smith and Baco 2003) and have been shown to be grazing the bone directly (Ellingham et al. 2017; Hoyoux et al. 2012), leaving behind deeply pockmarked surfaces. Tanner crabs have been observed to destroy and consume bones containing *Osedax* worms (see below), probably preying on the worms themselves (see Braby et al. 2007 and their supplemental video footage). Nevertheless, this can lead to rapid destruction of bones that have already been weakened by the boring activities of other invertebrates. This type of bioerosion does not create distinctive traces but leads to a general erosion of friable parts of the bone.

Worm Borings

Annelids are some of the most prolific borers of hard substrates in the marine realm, particularly polychaetes worms of the Spionidae and the Cirratulidae families. Their borings have been well studied because of their economic significance as blight on oyster shells (Blake and Evans 1973), as well as their paleontological and ecological significance. The borings may take a variety of forms but are typically U-shaped with two openings at the surface. Almost all worm borings are thought primarily to be protective domiciles, since very few hard substrates can provide nourishment. The shell-boring spionid polychaetes are known to orient their excavations with feeding currents or those created by the host, affording some nutritional benefits to the organism. Despite the ubiquity of polychaete borings in calcareous substrates, only one highly specialized genus of these worms has been recorded boring into bone.

Osedax (literally "bone devourers") worms subsist entirely on the skeletal remains of vertebrates on the seabed (Figures 7.20 and 7.21). Initially described from whale skeletons, they also have been documented living on experimentally implanted pig, cow, and fish

Figure 7.20 Close-up of *Osedax* worms living on whale bone.

bones (Jones et al. 2008; Rouse et al. 2011). There are over 20 known species of *Osedax* worms, mostly inhabiting deep waters below 100 m depth (Fujikura et al. 2006; Glover et al. 2005, 2008; Higgs et al. 2010; Rouse et al. 2004, 2008, 2009; Vrijenhoek et al. 2009); however, a few specimens have been found living on bones at 30 m during winter at high latitudes (Dahlgren et al. 2006). These worms have been recorded in deep waters of most of the world's oceans, and some species have been found on both sides of the Pacific. They can colonize bones within two months and occur in high densities, up to 30/cm^2 (Braby et al. 2007; Goffredi et al. 2004). The worms remain in the same place once they begin to bore into the bone and do so using specialized root tissue that releases a combination of acids and proteolytic enzymes, capable of dissolving the bone's collagen/mineral matrix (Higgs et al. 2011b).

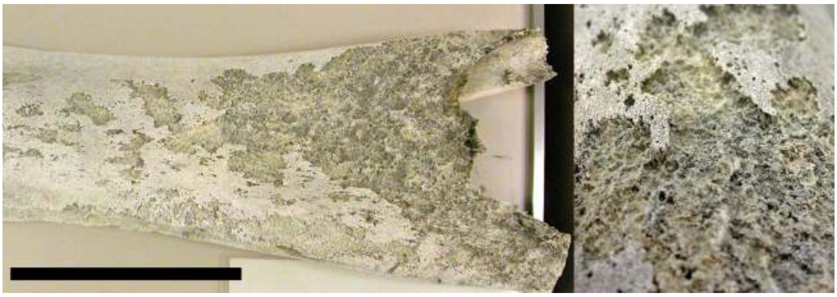

Figure 7.21 A whale bone after colonization by *Osedax* worms. Inset to the right shows a close-up of the pitted texture of the bone's surface where numerous borings have merged and the surface layer of bone has eroded. Bore holes can be seen in intact bone at the top of the inset. The scale is 10 cm.

Mollusk Borings

At least nine families of bivalve mollusks (phylum Mollusca, class Bivalvia) are known to bore into hard substrates, using both chemical and mechanical boring techniques (reviewed by Savazzi 1999). Pholadid bivalves (piddocks) are particularly versatile and have been found in various types of rock, shells, wood, coal, lead, concrete, and plastic. Especially pertinent is the report that they have been found boring into "recent and fossil bone" (Savazzi 1999:210). This is further supported by evidence of bivalve borings in fossil bone. In most cases, it has not been possible to tell if the borings occurred in bones before or after they had become fossils (e.g., Boreske et al. 1972; Tapanila et al. 2004); however, evidence presented by Belaústegui et al. (2012) seems to show that bivalve borings do occur in pre-fossilized bone.

Typically, boring bivalves create flask-shaped (clavate) borings that have a narrow neck leading from a surficial opening that smoothly tapers into a rounded interior chamber (known as *gastrochaenolites* in the paleontological literature). From the exterior, bivalve borings appear as holes in the bone's surface and can vary in outline from round to an hourglass shape to two adjoining holes, depending on the degree to which the two tubes leading from the chamber of the boring are merged (Kelly and Bromley 1984). Some species produce a calcareous lining to their borings, which may be useful in determining the identity of the bivalve that created the boring if the organism has since perished.

Sponge Borings

Rock boring demosponges (mainly in the family Clionaidae) are common bioeroders and can cause significant damage to calcareous hard substrates and skeletal material. They are found throughout tropical and temperate seas in both shallow and deep environments, but they tend to be most prolific down to ~70 m depth. Despite their ubiquity in marine environments, sponges rarely have been documented on submerged bones. A single record comes from human skeletal remains found in a 200-year-old shipwreck at 33 m depth off of Australia (Steptoe and Wood 2002).

Sponge boring is carried out at a cellular level where sponge tissue comes into contact with the surface of its host substrate (Pomponi 1980). Cellular projections chemically penetrate the substrate and then join up to encapsulate a small fragment or chip. Once surrounded, the fragment is detached and mechanically ejected through the exhalent papillae. Interestingly, this process shows many similarities to the mechanism by which osteoclasts in human bodies resorb bone during the process of remodeling (Pomponi 1980). As the sponges grow into the substrate, they create a network of inter-linked subsurface chambers, which are connected to the surface via a series of canals where the sponge's siphons stick out. Rates of excavation by sponges can vary depending on the density and composition of the substrate and on the supply of food available (Calcinai et al. 2007).

From the bone's surface, sponge borings appear as small round holes, similar to those produced by *Osedax* worms, but several features distinguish the two. First, because the exhalent and inhalant siphons of the sponge are of contrasting sizes, there are usually many small holes, accompanied by a few relatively large holes. Second, the holes created by sponges occur in a much more regular pattern across the bone's surface rather than the haphazard pattern of *Osedax* borings. The surface layer of sponge borings also may collapse, leaving a large pit of eroded bone, at which point the trace is very similar to *Osedax* borings. Sponge borings described by Steptoe and Wood (2002) were similarly eroded.

In this case, only the remnants of actual sponge tissue allowed identification of the organism responsible for the damage.

Effects of Large Vertebrate Predators and Scavengers

Apart from the massive soft tissue damage that large marine predators and scavengers can cause to a human body, they also may leave traces upon bone in the form of digestive corrosion and tooth marks as other species do (Chapters 9 and 19). These effects have been little researched among marine environments due to the obvious difficulties of retrieving altered bone under these extreme field circumstances. Even post hoc analyses are limited by the numbers of known cases of shark or other marine species feeding upon humans. Ihama et al. (2009) also noted the lack of autopsy data, due to the rarity of attacks, the frequent lack of recovery of known victims, and states of advanced decomposition making the assessment of trauma patterns difficult. These attacks are relatively rare despite their reputation to the contrary (Bendersky 2002), although attacks or at least the reporting thereof seem to be increasing in recent years due to increased human population and water activity (Clua and Reid 2013; West 2011). Lentz et al. (2010) examined a sample of 96 documented shark attacks dating since 1921 for which complete medical records were available and found that only 8.3% were fatal. Bites were found to be often very minor, ranging up to large amounts of soft tissue loss leading to death, frequently through exsanguination and shock.

The most aggressive species toward humans worldwide are great white sharks (*Carcharodon carcharias*), tiger sharks (*Galeocerdo cuvier*), and bull sharks (*Carcharhinus leucas*), with several other species known to attack humans in more isolated occurrences (Bury et al. 2012; Byard et al. 2006; Clua and Séret 2010; Ihama et al. 2009; International Shark Attack File 2021; Martin et al. 2009; Nakaya 1993; Rathbun and Rathbun 1997; Ritter and Levine 2005; Rtshiladze et al. 2011; West 2011). Other, smaller species of shark are known at least to scavenge upon human remains, including the cookiecutter shark (*Isistius brasiliensis*) (Ellingham et al. 2017; Ribéreau-Gayon et al. 2018), and it is likely that other species may engage in this behavior, thus expanding the pool of possible taphonomic agents. Great white, tiger, and bull sharks grow to relatively large sizes, making their feeding behavior inherently more damaging and less survivable. Great white sharks are among the largest predators known, and their maximum bite force of approximately 4000 lb may be the highest of any extant species (Wroe et al. 2008; Chapter 9). Shark teeth among all predatory species, however, are relatively fragile and grow in multiple lines (series) attached to the mandibles by flexible tissues. As teeth are lost, new teeth rotate forward to take their place in the same row (Figure 7.22). Feeding does not involve mastication so much as shredding by shaking the head laterally to rip through soft tissue with these sharp, often serrated teeth. The teeth tips penetrate the soft tissue, then the lateral movement of the head slices the distally and mesially facing margins of the teeth through it, shredding it and allowing detachment (Whitenack and Motta 2010). Sometimes, this behavior is directed at assessing an object as a potential food source, so soft tissue is greatly damaged, while little is actually consumed (Byard et al. 2000; Ritter and Levine 2005). Shark attacks often terminate after this initial trauma. In some attacks, more substantial amounts of soft tissue are removed (Clua et al. 2014; Clua and Reid 2013), leading to death. When consumption is pursued, chunks of soft tissue or whole smaller species or juveniles are swallowed, and whole teeth or fragments thereof are sometimes left in wounds (Ihama et al. 2009; İşcan and McCabe 1995; Lentz et al. 2010). Subsequent decomposition or movement in ocean water may cause many of these left-behind teeth to be lost prior to recovery.

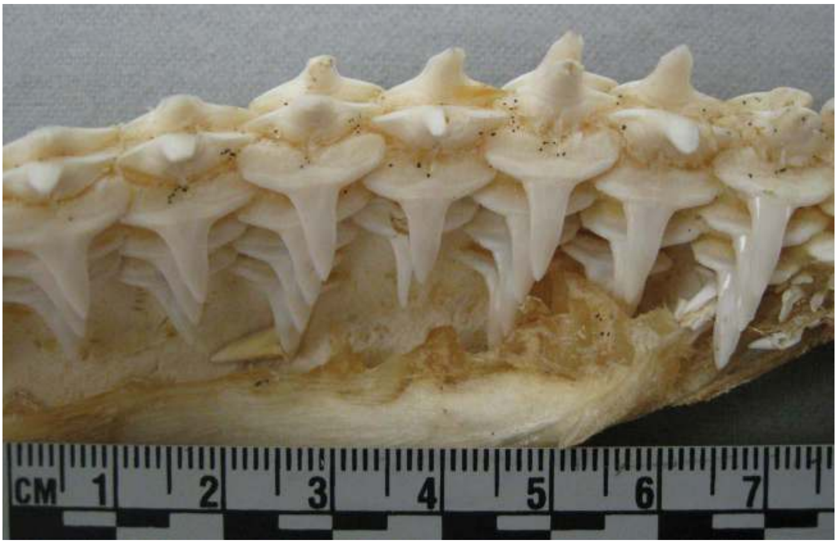

Figure 7.22 Mandible of blacktip reef shark (*Carcharhinus melanopterus*) showing multiple lines (series) of replacement teeth emerging in rows posterior to the front series. The teeth in this species lack serrations.

This pattern of feeding behavior is why shark bites tend to be so jagged through remaining soft tissue, with often a crescent-shaped area of removed flesh (Clua and Reid 2013; Ihama et al. 2009). Smaller sharks of any species would find it difficult to crush through large mammal bones (including humans), since their feeding structures are not morphologically adapted for this purpose. Traumatic lesions are often confined to the soft tissue, and any alteration of bones can be minor even when accompanied by large amounts of soft tissue damage (Byard et al. 2000; Clua and Reid 2013). Severing of body parts usually occurs at joints, with very little crushing or breakage of bone detected, except damage to ribs (Clua and Reid 2013; Ihama et al. 2009). Bites from predation are often directed at human legs and abdominal areas, as these areas are often lowest in the water among swimming humans as the shark approaches from below (Ihama et al. 2009; Ritter and Levine 2005). Ihama et al. (2009:219) noted that the characteristics of shark bites into soft tissue include incision without abrasion, wounds with serrated edges, a triangular or rectangular flap of skin left behind at the wound site, and a regular arrangement of marks that correspond to the spacing of shark teeth. Large portions of a human can be swallowed whole, as in the case examined by İşcan and McCabe (1995) from the coastal waters of Florida, where a tiger shark swallowed a likely intact leg and at least the intact femoral portion of the other leg.

Some species of shark frequently prey upon marine mammals (LeBoeuf et al. 1982; Lucas and Stobo 2000), and instances of attacks upon humans may be in part due to humans being mistaken for this prey, especially where humans in dark-colored wet suits (surfers and divers) present a form even more like the other prey species. These include pinnipeds (walruses, fur seals, true seals, and sea lions), which are frequent shark prey, especially juvenile pinnipeds. Great white sharks are a frequent pinniped predator, as indicated by the analysis of their stomach contents (LeBoeuf et al. 1982). As among humans, many shark attacks are survived, as indicated by the frequency of bite marks on living pinnipeds.

Figure 7.23 Examples of teeth of (left to right) common species of shark known to attack and/or consume humans: bull (*Carcharhinus leucas*), tiger (*Galeocerdo cuvier*), great white (*Carcharodon carcharias*), and mako (*Isurus* sp.) shark. Note that size variations displayed here are largely due to the body size attained by the individual sharks and are not interspecific indicators.

Shark tooth morphology and size varies by taxon (and individual) and can be identified even to species level in some cases from teeth alone. Overall shapes range from broadly triangular, to more sloped (tip angled, with one margin indented), to dagger-like, and these morphological types correspond to broad classes of feeding behavior (Whitenack and Motta 2010). In addition, some species' tooth margins are serrated in characteristic patterns (Nambiar et al. 1996), while others present a sharp, unserrated edge. Examples from common species with different tooth morphologies are depicted in Figures 7.23 and 7.24. Great white shark and bull shark teeth are triangular and broad, with serrated edges. The crown of tiger shark teeth has an indentation and multiple small cusps, with overall serrated edges. Mako shark (*Isurus* spp.) teeth are dagger-shaped and non-serrated. Hammerhead shark (*Sphyrna* spp.) teeth are intermediate in morphology between those of tiger sharks and mako sharks, with a serrated edge. Minor variations in morphology and size are also encountered based upon location of the tooth in the shark's mouth, based upon maxillary or mandibular and mesial to distal location (Nambiar et al. 1996; Ritter and Levine 2005). As indicated above, shark teeth or fragments thereof can be left behind in soft tissue (Anderson et al. 2003; Stock et al. 2017), making it possible to identify the consuming species directly and not just by inference from the bite mark morphology or from witness statements. The interdental distance (i.e., the distance between teeth) and the bite circumference (i.e., overall size of the mouth) can be used to estimate the species of shark and its body length (Clua et al. 2014; Clua and Reid 2013; Jublier and Clua 2018; Lowry et al. 2009; Stock et al. 2017). Nambiar et al. (1991) noted a general correlation between bite and tooth mark size and the overall body length of great white sharks causing the trauma.

In some cases, direct alterations to human bones from shark feeding do occur (Allaire et al. 2012; Allaire and Manhein 2009; Stock et al. 2017). Ihama et al. (2009) examined 12 cases of shark attack and/or scavenging from the waters off Okinawa, Japan, and noted that seven of these cases retained tooth marks on bones. The large species involved with these cases were most likely tiger sharks and bull sharks. Stock et al. (2017) compiled data from six cases in Florida, USA, and all six cases had some tooth markings, even the case that was recovered from a tiger shark's stomach. Multiple researchers have noted the presence of distinctive shark tooth markings or patterned damage in objects associated with victims.

Figure 7.24 Examples of teeth of (clockwise from upper left) common species of shark known to attack and/or consume humans: bull (*Carcharhinus leucas*), tiger (*Galeocerdo cuvier*), mako (*Isurus* sp.), and great white (*Carcharodon carcharias*) shark. Note the variations in serration pattern that potentially could leave marks on bone, including the lack of serrations of mako teeth. Scales are in mm.

These objects include surf boards, clothing, wetsuits (Ihama et al. 2009), and other diving equipment (Byard et al. 2006).

The damage to bones most frequently consists of parallel striations (linear marks not penetrating the cortical layer) or furrows (linear marks penetrating the cortical layer) (see Chapter 9, this volume, for a discussion of terminology of carnivore tooth marks). These are caused by multiple teeth margins simultaneously scraping across the surface of the bone (Anderson et al. 2003; Byard et al. 2000, 2002; Ihama et al. 2009; İşcan and McCabe 1995; Stock et al. 2017). Allaire and Manhein (2009) and Allaire et al. (2012)

Figure 7.25 Tooth striation on a human clavicle likely fed upon by bull shark (*Carcharhinus leucas*) in the Gulf of Mexico. (From Allaire et al. 2012:1676; used with permission, John Wiley and Sons.)

go into more detail in describing the types of dental markings left by shark feeding on a body recovered from the Gulf of Mexico. They noted the following types of bone trauma: (1) punctures without associated fractures, caused by teeth entering the bone in a straight-on tooth impact; (2) punctures with associated fractures, caused by teeth entering weaker portions of bone (ribs, etc.) in a straight-on impact and creating compression fractures; (3) striations with bone shaving, where the margin of the tooth scraped a protuberance of the bone then slid off (Figure 7.25); (4) overlapping striations (Figure 7.26), caused by multiple passes with the teeth in the same location as the shark's head shakes from side to side; and (5) incised bone gouges. The striations in this case indicated that a species with serrated tooth margins was responsible for some of the damage, with the size and patterning indicating that a bull shark was likely involved, with other areas of damage possibly caused by much smaller requiem sharks (*Carcharhinus* spp.).

Traces of shark teeth scraping across bones of marine mammals also are known paleontologically (Bianucci et al. 2010; Ehret et al. 2009; Kallal et al. 2012), which is unsurprising given the ancient fossil history of sharks and the diversity of potential prey items. Shark feeding upon humans also has been reported as far back as 1370 BC in Okayama, Japan (White et al. 2021). Due to their cartilage skeletons, most direct traces of shark fossil history are confined to their ossified teeth. The pattern of serrations incised into bone by shark teeth may be identifiable to taxa of various levels. Nambiar et al. (1996) examined whole jaw sets of great white shark from three individuals (two adult and one juvenile). They found that the serration patterns varied from tooth to tooth within the same individual, including peaks that were bifid and trifid, with neither consistent overall pattern in serration size nor arrangement. Individual serration peaks also tended to get fractured away, further altering the potential pattern of individual tooth marks during the life of the

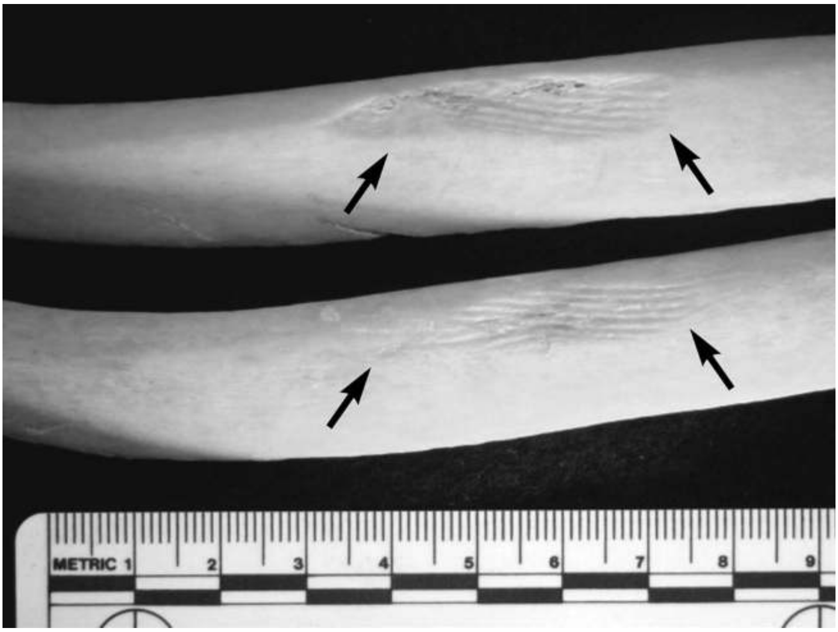

Figure 7.26 Human ribs likely fed upon by bull shark (*Carcharhinus leucas*) in the Gulf of Mexico. Note the gouged surfaces with parallel striations (arrows), which could be used to eliminate some species of shark as potential scavengers (see Figures 7.23 and 7.24). The scale is in mm. (From Allaire et al. 2012:1676; used with permission, John Wiley and Sons.)

shark. They also noted the variations of tooth size and form within each specimen, with the largest teeth mesial, and that some areas of the mandibular teeth of the juvenile had no serrations or very small ones.

It is unknown the degree to which sharks may scavenge human remains, and available data indicate that shark digestion is a slow process when they do. Rathbun and Rathbun (1997) noted the (serendipitous) find of partial human remains (left knee portion; see Figure 7.27) in the stomach of a tiger shark, which is one of the few shark species known to scavenge frequently, including human remains (Anderson et al. 2003). They were able to trace the possible origin of the remains back to a jetliner crash in the general (coastal North Atlantic) vicinity earlier in the same month. The trauma separating the femur in this case may have occurred as a result of the air crash (or other unknown source), although the tibia did have clear scoring from shark teeth (T. Rathbun, pers. comm.). Stock et al. (2017) reported that human remains recovered on the shore of Florida, USA, had shark damage and were identified as a person who had likely undergone a massive deceleration event and therefore was already dead when encountered by the shark. İşcan and McCabe (1995) noted that the portions of human legs recovered from a tiger shark, also off the coast of Florida, that they examined may have been scavenged. An infamous homicide case (Castles 1995) from 1935 in Sydney, Australia, included human remains that were consumed by a tiger shark. A human left arm, complete with identifiable tattoo and manila rope around the wrist, was regurgitated by a 4-m tiger shark recently brought for display to an aquarium. This tiger shark, the first live one on display in the world, was found to have consumed *another*, smaller shark that may have consumed the human arm first. This likely crudely dismembered arm probably had been disposed of in the nearby ocean in an attempt to

Figure 7.27 Human remains (knee portion), after removal of adhering soft tissue, recovered from a tiger shark (*Galeocerdo cuvier*) stomach off the coast of North Carolina, USA. The lower scale is in cm. (Image courtesy of T. Rathbun, personal collection.)

hide evidence of a homicide and so must have been scavenged. (Other evidence pointed to the victim being murdered and dismembered on land.) Identifiable remains therefore persisted in this case for a minimum of 8 days in the tiger shark's stomach and as long as 17 days (from the date that the victim was last seen alive). The state of preservation was such that the victim's fingerprints could be obtained and were used for positive identification, along with the tattoo. Ihama et al. (2009) and Makino et al. (2004) noted cases of probable suicide victims who were later recovered with traces of shark feeding trauma, and Ihama et al. (2009) further noted one case of a floating corpse that was witnessed to receive subsequent shark scavenging. Byard et al. (2002) noted a case of accidental drowning that also bore these traces. Scavenging therefore occurred in at least some of these cases after death had occurred. A variety of shark species are suspected in these cases, including cookiecutter shark (*Isistius* sp.) (Makino et al. 2004) and what must have been larger species.

Some species of sharks have been found to practice gastric eversion, or the pushing of their stomachs inside-out and partially outside of their mouths (Brunnschweiler et al. 2005, 2011). This behavior fills the same role as peristaltic vomiting in mammals, and it may be common. The purpose may be the ejection of indigestible stomach contents, including bone or debris swallowed accidentally, and thus in practice, it is analogous to the vomiting of pellets as practiced by numerous species of avian raptors, including owls and many hawk, eagle, falcon, and other diurnal species (Chapter 16). Ejection of indigestible stomach contents among taxa is frequently encountered where prey is swallowed whole or with minimal mastication and among scavenging species (including, among terrestrial scavengers, hyenas) where marginal nutrition sources may be consumed in large amounts. The lack of mastication may be compensated for in part through very high shark stomach acidity, which has been measured as low as a pH of 0.4 (Papastamatiou et al. 2007). Shark gastric eversion is little understood in terms of frequency, timing within the digestion process, or variations by species. In terms of forensics, it makes recovery of partial human remains less likely, given that after digestion of most soft tissues, the remaining portions will be less likely to be recovered: many cases of shark consumption of humans are discovered only after the shark has been killed and its stomach contents examined. It also means that isolated human remains bearing shark tooth marks may have been consumed previously, as a result of predation or scavenging, and may have been transported a great distance from the initial location of feeding. This increase in distance between discovery and initial feeding greatly increases the potential pool of deceased individuals and decreases the likelihood of their identification.

Massachusetts, USA Forensic Sample

Pokines and Higgs (2015) examined a sample (n = 25) of fully or mostly skeletonized marine cases from the shoreline of or ocean adjacent to Massachusetts, USA, plus some cases from nearby marine waters brought in by fishing vessels that home port in this state. This sample (Table 7.1) has been increased (total n = 40) by additional skeletonized cases recording the same taphonomic effects (Table 7.2). The majority of cases were isolated bones, which made up 33 of the 40 cases (82.5%). Even isolated bones can be caught in fishing nets or scallop rakes, so these cases do not universally come from shoreline contexts. The smallest isolated remains were mandibles, and the only isolated long bones were tibiae and femora, so the recovery of small, less-distinctive isolated bones appears to be an unlikely occurrence. The mandibles may look much more distinctively human to passers-by on the shore, which may boost their rates of recovery and reporting to law enforcement (Pokines et al. 2017); all had at least one tooth present. Isolated cranial vaults (n = 10) made up 25.0% of the sample, with an additional case of a partial vault with vertebrae C1–3 still articulated (2.5%) and two isolated crania (5.0%), so these types of remains must be both survivable and recognizable. A total of five cases (12.5%) were partial skeletons of some kind, and one case was a tibia and a fibula, recovered accidentally by a fishing net.

Table 7.1 Skeletal Representation of Forensic Cases (n = 40) from Coastal Massachusetts, USA

Portions Present	n	%
Tibia	8	20.0
Tibia, fibula	1	2.5
Femur	9	22.5
Innominate	1	2.5
Partial postcranial	1	2.5
Cranium, partial postcranial	4	10.0
Partial vault	10	25.0
Partial vault + C1-3	1	2.5
Cranium	2	5.0
Mandible	3	7.5
TOTAL	40	100.0

Source: Pokines and Higgs (2015) and new data. Used with permission, *Journal of Forensic Identification*.

Table 7.2 Taphonomic Characteristics of Forensic Cases (n = 40) from Coastal Massachusetts, USA

Characteristic	n	%
Physical changes		
Soft tissue also present	7	17.5
Bone surface condition		
Chalky	12	30.0
Organic sheen	28	70.0
Fat leaching	16	40.0
Adipocere	12	30.0
Battering/rounding	37	92.5
Windowing	8	20.0
Bleaching	34	85.0
Mineral staining		
Reddish	11	27.5
Dark	8	20.0
Adhering/embedded sediments		
Sand	25	62.5
Silt	5	12.5
Adhering taxa		
Mollusks	4	10.0
Mollusk scars	6	15.0
Barnacles	13	32.5
Barnacle scars	4	10.0
Other Crustacean	1	2.5
Algae (all types)	15	37.5
Bryozoa	3	7.5

Source: Pokines and Higgs (2015) and new data. Used with permission, *Journal of Forensic Identification*.

General bone preservation was variable and likely dependent upon the duration of marine immersion and other factors which may include degree of scavenging, water temperature, distance of transport, exposure to high-energy environments, type of substrate, and amount of time buried in sediment (see "Estimation of the PMSI from Bone Changes" section, below). A total of 16 cases (40.0%) had visible fat leaching from the bones (Figure 7.8), with seven cases (17.5%) also having some decomposing soft tissue (due in part to the criteria for selection including at least a mostly skeletonized state). Twelve cases (30.0%), independent of any leaching fat, displayed traces of adipocere, either adhering to the bone surface or embedded in exposed cancellous bone (Figure 7.1). Surface condition independent of fat leaching was recorded as either chalky (n = 12; 30.0%) or retaining an organic sheen (n = 28; 70.0%).

Battering and rounding of surfaces was prevalent among this sample (n = 37; 92.5%). This high degree may in part be due to the high proportion of isolated bones, which had detached from their bodies and therefore could be tumbled about freely in marine sediments and against rocks. Battering (Figures 7.2 and 7.3) included some cases with multiple random striations and or sometimes fractures. Battering/rounding cases included eight (20.0%) that also had *windowing*, the creation of a hole through a bone or expansion of an existing foramen from gradual surface attrition.

Figure 7.28 Two acorn barnacles identifiable to species, bay barnacles (*Amphibalanus improvisus*), marine context, Massachusetts, USA.

Mineral stains on bone surfaces were common, categorized as reddish (n = 11; 27.5%) or dark (n = 8; 20.0%). The former is likely due to some combination of iron oxides, and the latter likely indicates the presence of iron sulphides. Adhering/embedded sediments (sand, n = 25; 62.5% or silt, n = 5; 12.5%) also were common. These were either adhering to the surface or embedded in pore spaces.

Adhering taxa were common overall. Four cases (10.0%) retained adhering mollusks (Figure 7.16), and six cases (15.0%) had mollusk homing scars (Figure 7.17) where mollusks had formerly adhered. Barnacle encrustation was common, with 13 cases (32.5%) having acorn barnacles still adhered to the bone (Figures 7.12 and 7.13), and four cases (10.0%) having barnacle scars. Two common species of acorn barnacle were identified overall, *Amphibalanus improvisus* (Figure 7.28) and *Semibalanus balanoides*. The former species has a calcified shell base and the latter species has a membranous one, so the scars that they leave on substrates are very distinguishable, along with other differences in their morphology. Only one case (2.5%) was associated with an additional crustacean taxon, a small crab (Decapoda) contained inside a cranial vault. This taxon likely will be associated with human remains only where they are still feeding upon soft tissue or are trapped inside soft tissue or bone spaces, since they do not adhere to bone like barnacles. A total of 15 cases (37.5%) had some form of algae adherence, ranging from diffuse green surface staining of single-celled protist types to larger forms such as seaweed or filamentous brown algae. Three cases (7.5%) had bryozoan colonization on bone surfaces (Figure 7.11).

Estimation of the PMSI from Bone Changes

Multiple researchers (see "Estimation of the Postmortem Submergence Interval [PMSI] from Decomposition" section, above) have addressed this question, but less research has been applied to estimating PMSI from direct changes to bones after they have been exposed from decomposition and are then more susceptible to accruing the taphonomic effects described above.

Marine Abrasion Stages

Other researchers have developed scales of bone abrasion, primarily to analyze the fluvial origins of fossil deposits. Fiorillo (1988) developed a 0–3 scale for fossils that was derived from sedimentological scales of roundedness, with Stage 0 comparable to very angular and Stage 3 comparable to rounded. Boessenecker et al. (2014) modified Fiorillo's (1988) scale, which proceeded from Stage 0 (unabraded), to Stage 1 (lightly abraded), and Stage 2 (heavily abraded). Davies et al. (1990) developed a similar scale of rounding and abrasion of mollusk shells. As discussed above, Fernández-Jalvo and Andrews (2003, 2016) developed a 0–24 scale that included slight, moderate, heavy, and extreme rounding of bone. Sorg et al. (1997), however, included a four-stage scale for marine rounding of bone in forensic cases: absence of abrasion, cortical thinning only, cancellous bone exposure, and marrow cavity exposure.

Pokines et al. (2020) produced a set of marine abrasion stages (Table 7.3) in order to codify this taphonomic effect for standardized forensic data gathering. These were derived from experimental abrasion of already dry white-tailed deer (*Odocoileus virginianus*) bones (n = 115) in a tumbler with salt water and sand or small rocks as abrasives, over varying intervals. These stages follow the gradual loss of the cortical bone surface as a bone is abraded, which leads to margins rounding and minor areas of cancellous bone exposure gradually expanding until the outline of the bone begins to be altered. Breakage can accompany this gradual abrasion alteration, especially at its later stages as the bone's integrity begins to fail, but substantial breakage can occur during relatively brief episodes before or during the overall agitation and transport process. Newly exposed break surfaces then may begin to undergo their own gradual abrasion, and their rounding would be considered for abrasion score; prior trauma would not be. Bone can undergo high degrees of abrasion without fracturing, especially long bones, and also be fractured without showing abrasion. Fracturing itself is therefore not considered part of the 0–4 abrasion stage scoring system.

Each element should be assigned an abrasion score by its most advanced stage (Pokines et al. 2020). Stage 0 elements are unabraded. Stage 1 elements (Figure 7.29) have only very

Table 7.3 Abrasion Stages for Marine Bones

Stage	Description
0	Unrounded; soft tissue may still adhere. Note: fracturing may occur at any stage, even at 0.
1	Beginning rounding of margins; soft tissue may still adhere.
2	Moderate rounding of margins, with minor cancellous bone exposure appearing on sharp margins/most projecting points. Dense soft tissue may still adhere.
3	Heavy rounding of margins; significant cancellous bone exposure may appear on broader margins and greater cancellous bone exposure on sharper margins, but the basic bone outline and contours of surface structures are still present. Adhering soft tissue generally not present from this stage forward. Perimeter outline of the bone still present but with some modification.
4	Severely rounded, with extremities removed; may have marrow cavity exposure and/or loss of most surface features. Perimeter outline altered.

Source: Pokines et al. (2020). Used with permission, *Forensic Anthropology*/University of Florida Press.

Figure 7.29 Experimentally derived marine abrasion scale illustrated by radii of white-tailed deer (*Odocoileus virginianus*). Left to right, stage 0, 1, 2, 3, and 4 rounding. The scale is in cm.

minor abrasion: the cancellous bone is not exposed, but some visible rounding of cortical bone margins has occurred. Some soft tissue, typically connective, may still adhere. Stage 2 elements have only minor cancellous bone exposure, which normally appears along the sharper margins first. The persistence of soft tissue adherence was rare past this stage. Stage 3 elements have significant cancellous bone exposure, often with different patches from more exposed margins or projections having coalesced. Stage 4 elements are characterized by rounding, where the extremities of the bones have been worn away, especially processes and other surface morphological features that stick out the farthest. They also may have marrow cavity exposure. Elements can advance beyond stage 4 marine abrasion, as in the cases where a bone has completely disintegrated (noted to happen experimentally). In practical terms, bones reduced to tiny fragments are unlikely to become a forensic case on their own unless marine archaeological procedures were employed to recover them.

Sample of Forensic Cases from Massachusetts, USA

The marine abrasion stage system derived above was applied to a sample (n = 12) of marine forensic cases from the Office of the Chief Medical Examiner, Massachusetts, USA (Table 7.4) that had known postmortem intervals (Pokines et al. 2020). Massachusetts has a long history of shipwrecks along its coast (National Park Service 2020), so some unidentified remains could come from non-modern contexts. The identified cases all consisted of isolated remains or clusters of remains that were recovered after washing ashore or were caught in a fishing net. In some of the cases examined, bones were recovered at different times matching the same individual, so the advancement of marine abrasion for bones of the same individual could be examined. More data points therefore could be collected, since the separate recoveries from the same individual could be assessed separately. Three cases were individuals whose remains were recovered at intervals and identified to be the same person, although that person is still unidentified; hence, the absolute PMSI is unknown, just the interval between bone recoveries. Other data regarding marine taphonomic effects (Pokines and Higgs 2015) also were collected regarding the timing of their appearance among the cases. Sorg et al. (1997) conducted similar research in the Gulf of

Table 7.4 **Marine Taphonomic Changes to Skeletal Cases from the Office of the Chief Medical Examiner, Boston, Massachusetts, USA**

				Damage			Decomposition			Bone Bleaching			Bone Texture		Staining		Biological Adherence			
Case	Recovery	Interval (Months)	Inventory	Degree of Abrasion	Fracturing	Windowing	Soft Tissue	Fat Leaching	Adipocere	None	Partial	Extensive to full	Organic Sheen	Chalky	Red Mineral	Dark Mineral	Mollusks	Barnacles/ Scars	Algae	Bryozoa
1	Net	10	Tibia, fibula	1				X				X		X			X	X		
2	Shore	2	Cranium, partially skeletonized body	0			X			X			X							
2	Shore	2	Ribs (4)	0			X			X			X							
2	Shore	24	Tibia	3				X	X			X	X		X				X	
2	Shore	40	Mandible	3	X	X						X	X					X	X	X
3	Net	30	Tibia	3	X			X	X			X		X	X		X	X		
4	Shore	N/A	Partial postcranial skeleton	0			X	X			X		X							
4	Shore	3*	Scapula, rib	1		X	X	X			X		X							
4	Shore	4*	Mandible	1								X	X						X	
4	Shore	5*	Maxilla	2	X							X	X							
5	Net	N/A	Femur	2				X	X			X		X		X		X	X	
5	Net	35*	Femur	3					X			X		X	X	X		X	X	X
6	Net	8	Cranium, partial postcranial skeleton	1			X	X	X		X		X					X	X	
7	Shore	N/A	Innominate	1				X	X		X		X		X		X			
7	Shore	42*	Partial cranium	2	X	X						X	X							
8	Net	6	Cranium	1				X				X	X							
9	Shore	7	Partial cranium, C1-C3	1	X		X	X		X			X							
9	Shore	33	Innominate	3	X	X						X		X			X	X	X	
10	Shore	19	Innominate	3	X							X	X							
10	Shore	19	Femur	2							X		X			X				
10	Shore	23	Mandible	2								X	X		X				X	
10	Shore	44	Femur	3				X				X	X							
11	Net	8	Cranium	1	X			X				X	X						X	
12	Shore	55	Tibia	4				X	X			X	X							

Source: Pokines et al. (2020). Used with permission, *Forensic Anthropology*/University of Florida Press.

*Months elapsed since recovery of first remains for that case.

Figure 7.30 Distal tibia rounded to marine abrasion stage 4, marine context, Massachusetts, USA. The scale is in cm.

Maine, north of Massachusetts, on a sample (n = 13) of marine cases, and those findings are compared below.

The Massachusetts OCME (Table 7.4) sample showed a clear progression of abrasion stage relative to the PMSI. A Spearman rank-order correlation coefficient for individual recoveries of remains (n = 15) with a known PMSI was calculated relative to the marine abrasion scale, resulting in a $\rho_s = 0.9448$, with $p < 0.000001$ (one-tailed), i.e., a highly significant correlation. Only one bone (an isolated tibia) had reached stage 4 in the OCME sample (Figure 7.30), and more remains at this abrasion stage had been noted to occur among cases in this jurisdiction. Sorg et al. (1997) noted one marine case with a PMSI of 140 months (11 years, 9 months) that had marrow cavity exposure attributable to abrasion/dissolution. Sorg et al. (1997) noted that bones could display no marine abrasion as late as 16.8 months, and that cancellous bone exposure (likely corresponding with marine abrasion stage 2 in the present system) appeared in a case with a PMSI of 7.9 months.

The relationships between PMSI and taphonomic effects besides abrasion in the Massachusetts OCME sample are also summarized in Table 7.5 (Pokines et al. 2020). Fractured bone was noted as early as seven months postmortem, and windowing, which sometimes accompanies advanced abrasion, was noted as early as 33 months postmortem. These results were similar to Sorg et al. (1997), who found cranial fracturing as early as 7.9 months postmortem, but this effect is at least in part bone morphology-dependent, with thinner areas of bone being more susceptible. A complete lack of adhering soft tissue was noted as early as six months postmortem in the Massachusetts OCME sample, similar to the findings of Sorg et al. (1997), who noted this state as early as 7.9 months postmortem. Relatedly, adhering soft tissue was noted to persist only as late as eight months in the Massachusetts OCME sample. Sorg et al. (1997) noted that adhering soft tissue could be retained as late as 18 months, and under special circumstance of burial in anoxic sea floor sediments soft tissue can persist for decades (pers. obs.). Fat leaching from inside the internal spaces of the bones showed up as early as six months postmortem and persisted as late as 55 months, although the fat leaching in the latter case was not highly visible upon accession and became much more pronounced during storage. (This phenomenon has been noted among other marine cases in storage.) Adipocere was noted on bones as early as 24 months postmortem and persisted in cases at least 55 months postmortem. As noted above, adipocere sometimes can be found embedded in exposed cancellous bone

Table 7.5 **Summary of the Timing of Taphonomic Changes Other than Marine Abrasion on Skeletal cases from the Office of the Chief Medical Examiner (OCME), Boston, Massachusetts, USA**

Taphonomic Alteration	OCME Earliest Manifestation (Months PMI)	OCME Latest Manifestation (Months PMI)	Sorg et al. (1997) Earliest Manifestation (Months PMI)	Sorg et al. (1997) Latest Manifestation (Months PMI)
Other damage (beyond abrasion)				
Fracturing	7	N/A	7.9	N/A
Windowing	33	N/A		
Decomposition				
Lack of soft tissue	6	N/A	7.9	N/A
Soft tissue adherence	N/A	8	N/A	18
Fat leaching	6	55*		
Adipocere	24	55	9.6	36.6
Bone bleaching				
None	N/A	7		
Partial	8	19		
Extensive to full	6	N/A		
Bone texture				
Organic sheen	N/A	55		
Chalky	10	N/A		
Staining				
Red mineral	23	N/A		
Dark mineral	19	N/A		
Biological adherence				
Mollusks	10	N/A	16.8	N/A
Barnacles/scars	8	N/A	16.8	N/A
Algae	8	N/A		
Bryozoa	40	N/A		

Source: Pokines et al. (2020). Used with permission, *Forensic Anthropology*/University of Florida Press.

[*] Minimal visibility when first acquired; more fat leached during storage.

(Figure 7.1), so it is likely that it can persist for much longer, perhaps over a decade under some circumstances. Sorg et al. (1997) noted the presence of adipocere in cases as recent as 9.6 months postmortem and as late as 36.6 months.

The timing of other bone effects also were noted (Table 7.5). A lack of marine bleaching persisted as late as seven months postmortem in the Massachusetts OCME sample, with partial bleaching visible as early as eight months postmortem and persisting as late as 19 months. Extensive to full bleaching (i.e., all external natural bone color gone; Chapter 12) appeared as early as 6 months postmortem. Retained organic sheen (i.e., the bone having a shiny texture similar to plastic) over at least some portions of the bone surface persisted as long as 55 months, but surfaces of some bones had turned to a dull, chalky texture after as little as 10 months. Mineral staining formed as early as 19 months (dark) or 23 months (red). Marine organism colonization showed up as early as 8 months (algae and [acorn] barnacles or barnacle scars) or 10 months (mollusks) postmortem. Sorg et al. (1997) noted one case that had colonization by mollusks and barnacles, which occurred at least by 16.8 months. Bryozoa did not show up until 40 months in the Massachusetts OCME sample.

Conclusions

Multiple environmental (mechanical, sedimentary, and chemical) and biological (adhesion, boring, and feeding) processes occurring commonly in marine environments alter osseous remains in ways that frequently are characteristic of this environment. The ultimate postmortem origin of osseous remains often can be traced by these taphonomic alterations to marine settings, specifically high-energy and high-biodiversity/biomass shallow coastal areas. This portion of the oceans (the littoral/euphotic zone) is frequented the most by humans and has the highest instance of the introduction and recovery of human remains over the open ocean (pelagic) or deep-water (benthic) zones. These same taphonomic processes also have the potential to allow estimation of the PMSI but require additional research in most cases to refine the successful application of these techniques.

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References

Allaire, M. T., and M. H. Manhein (2009) Shark-inflicted trauma on human skeletal remains. *Proceedings of the American Academy of Forensic Sciences* 15:317–318.

Allaire, M. T., M. H. Manhein, and G. H. Burgess (2012) Shark-inflicted trauma: A case study of unidentified remains recovered from the Gulf of Mexico. *Journal of Forensic Sciences* 57(6):1675–1678.

Allison, P. A., C. R. Smith, H. Kukert, J. W. Deming, and B. A. Bennett (1991) Deep-water taphonomy of vertebrate carcasses: A whale skeleton in the bathyal Santa Catalina Basin. *Paleobiology* 17(1):78–89.

Anderson, G. S. (2008) *Determination of Elapsed Time Since Death in Homicide Victims Disposed of in the Ocean*. Canadian Police Research Centre, Technical Report TR-10-2008, Ottawa, ON, Canada.

Anderson, G. S., and L. S. Bell (2014) Deep coastal marine taphonomy: Investigation into carcass decomposition in the Saanich Inlet, British Columbia using a baited camera. *PLoS ONE* 9(10):e110710. DOI: 10.1371/journal.pone.0110710.

Anderson, G. S., and L. S. Bell (2016) Impact of marine submergence and season on faunal colonization and decomposition of pig carcasses in the Salish Sea. *PLoS ONE* 11:e0149107. DOI: 10.1371/journal.pone.0149107.

Anderson, G. S., and L. S. Bell (2017) Comparison of faunal scavenging of submerged carrion in two seasons at a depth of 170 m, in the Strait of Georgia, British Columbia. *Insects* 8(33):1–15. DOI: 10.3390/insects8010033.

Anderson, G. S., and N. Hobischak (2002) *Determination of Time of Death for Humans Discovered in Saltwater Using Aquatic Organism Succession and Decomposition Rates*. Canadian Police Research Centre, Technical Report TR-09-2002, Ottawa, ON, Canada.

Anderson, B., A. Manoukian, T. D. Holland, and W. E. Grant (2003) A death in paradise: Human remains scavenged by a shark. In *Hard evidence: Case Studies in Forensic Anthropology* ed. by D. W. Steadman, pp. 189–196. Prentice Hall, Upper Saddle River, NJ.

Appleton, A. J., and R. C. O'Brien (2015) Obliteration of sharp force trauma artifact by high particulate water wash. *Proceedings of the American Academy of Forensic Sciences* 21:129.

Argast, S., J. O. Farlow, R. M. Gabet, and D. L. Brinkman (1987) Transport-induced abrasion of fossil reptilian teeth: Implications for the existence of Tertiary dinosaurs in the Hell Creek Formation, Montana. *Geology* 15(10):927–930.

Arnaud, G., S. Arnaud, A. Ascenzi, E. Bonucci, and G. Graziani (1978) On the problem of the preservation of human bone in sea-water. *Journal of Human Evolution* 7(5):409–420.

Ascenzi, A., and G. Silvestrini (1984) Bone-boring marine micro-organisms: An experimental investigation. *Journal of Human Evolution* 13(6):531–536.

Aslan, A., and A. K. Behrensmeyer (1996) Taphonomy and time resolution of bone assemblages in a contemporary fluvial system: The East Fork River, Wyoming. *Palaios* 11:411–421.

Bassett, H. E., and M. H. Manhein (2002) Fluvial transport of human remains in the lower Mississippi River. *Journal of Forensic Sciences* 47(4):719–724.

BEA (2011) *Interim Report no.3 on the Accident on 1st June 2009 to the Airbus A330-203 Registered F-GZCP Operated by Air France Flight AF 447 Rio de Janeiro—Paris*. Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile, Ministère de l'Écologie, du Développement Durable, des Transports et du Logement, Paris, France.

Beardmore, S. R., P. J. Orr, T. Manzocchi, H. Furrer, and C. Johnson (2012) Death, decay and disarticulation: Modelling the skeletal taphonomy of marine reptiles demonstrated using Serpianosaurus (Reptilia; Sauropterygia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 337/338:1–13.

Behrensmeyer, A. K. (1982) Time resolution in fluvial vertebrate assemblages. *Paleobiology* 8(3):211–227.

Behrensmeyer, A. K. (1988) Vertebrate preservation in fluvial channels. *Palaeogeography, Palaeoclimatology, Palaeoecology* 63:183–199.

Belaústegui, Z., J. M. de Gibert, R. Domènech, F. Muñiz, and J. Martinell (2012) Clavate borings in a Miocene cetacean skeleton from Tarragona (NE Spain) and the fossil record of marine bone bioerosion. *Palaeogeography, Palaeoclimatology, Palaeoecology* 323–325:68–74.

Bell, L. S., and A. Elkerton (2008) Human skeletal material recovered from the medieval warship *Mary Rose*. *International Journal of Osteoarchaeology* 18(5):523–535.

Bell, L. S., J. A. Lee Thorp, and A. Elkerton (2009) The sinking of the *Mary Rose* warship: A medieval mystery solved? *Journal of Archaeological Science* 36(1):166–173.

Bendersky, G. (2002) The original "Jaws" attack. *Perspectives in Biology and Medicine* 45(3):426–432.

Berkeley, A. (2009) Understanding the role of taphonomy and post-depositional processes on the intertidal stratigraphic record. *Palaios* 24:271–272.

Bessat, F., and D. Buigues (2001) Two centuries of variation in coral growth in a massive *Porites* colony from Moorea (French Polynesia): A response of ocean-atmosphere variability from south central Pacific. *Palaeogeography, Palaeoclimatology, Palaeoecology* 175:381–392.

Bianucci, G., B. Sorce, T. Storai, and W. Landini (2010) Killing in the Pliocene: Shark attack on a dolphin from Italy. *Palaeontology* 53(2):457–470.

Bixler, G. S., and B. Bhushan (2012) Biofouling: Lessons from nature. *Philosophical Transactions of the Royal Society A* 370:2381–2417. DOI: 10.1098/rsta.2011.0502.

Blake, J. A., and J. W. Evans (1973) *Polydora* and related genera as borers in mollusk shells and other calcareous substrates. *Veliger* 15(3):235–249.

Blanco Pampín, J., and B. A. López-Abajo Rodríguez (2001) Surprising drifting of bodies along the coast of Portugal and Spain. *Legal Medicine* 3(3):177–182.

Boessenecker, R. W., F. A. Perry, and J. G. Schmitt (2014) Comparative taphonomy, taphofacies, and bonebeds of the Mio-Pliocene Purisima Formation, Central California: Strong physical control on marine vertebrate preservation in shallow marine settings. *PLoS ONE* 9(3):e91419. DOI: 10.1371/journal.pone.0091419.

Boreske, J., L. Goldberg, and B. Cameron (1972) A reworked cetacean with clam borings: Miocene of North Carolina. *Journal of Paleontology* 46(1):130–139.

Bourget, E. (1980) Barnacle shell growth in relation to environmental factors. In *Skeletal Growth of Aquatic Organisms* ed. by D. C. Rhoads and R. A. Lutz, pp. 469–491. Springer, New York.

Bourget, E., and D. J. Crisp (1975) An analysis of the growth bands and ridges of barnacle shell plates. *Journal of the Marine Biological Association of the UK* 55(2):439–461.

Boyle, S., A. Galloway, and R. T. Mason (1997) Human aquatic taphonomy in the Monterey Bay area. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 605–614. CRC Press, Boca Raton, FL.

Braby, C. E., G. W. Rouse, S. B. Johnson, W. J. Jones, and R. C. Vrijenhoek (2007) Bathymetric and temporal variation among *Osedax* boneworms and associated megafauna on whale-falls in Monterey Bay, California. *Deep-Sea Research Part I* 54:1773–1791.

Braune, W., and M. D. Guiry (2011) *Seaweeds: A Colour Guide to Common Benthic Green, Brown and Red Algae of the World's Oceans*. Koeltz Scientific Books, Konigstein, Germany.

Britton, J. C., and B. Morton (1994) Marine carrion and scavengers. In *Oceanography and Marine Biology: An Annual Review* (Vol. 32) ed. by H. Barnes, A. D. Ansell, R. N. Gibson, and M. Barnes, pp. 369–434. University College, London Press, London.

Bromage, T. G. (1984) Interpretation of scanning electron microscopic images of abraded forming bone surfaces. *American Journal of Physical Anthropology* 64(2):161–178.

Bromley, R. G. (1994) The palaeoecology of bioerosion. In *The Palaeobiology of Trace Fossils*, ed. by S. K. Donovan, pp. 134–154. Wiley, Chichester, UK.

Bromley, R. G., and C. Heinberg (2006) Attachment strategies of organisms on hard substrates: A palaeontological view. *Palaeogeography, Palaeoclimatology, Palaeoecology* 232:429–453.

Brooks, S., and R. H. Brooks (1997) The taphonomic effects of flood waters on bone. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 553–558. CRC Press, Boca Raton, FL.

Brunnschweiler, J. M., P. L. R. Andrews, E. J. Southall, M. Pickering, and D. W. Sims (2005) Rapid voluntary stomach eversion in a free-living shark. *Journal of the Marine Biological Association of the U.K.* 85:1141–1144.

Brunnschweiler, J. M., F. Nielsen, and P. Mottac (2011) In situ observation of stomach eversion in a line-caught Shortfin Mako (*Isurus oxyrinchus*). *Fisheries Research* 109(1):212–216.

Bury, D., N. Langlois, and R. W. Byard (2012) Animal-related fatalities-Part I: Characteristic autopsy findings and variable causes of death associated with blunt and sharp trauma. *Journal of Forensic Sciences* 57(2):370–374.

Byard, R. W., J. D. Gilbert, and K. Brown (2000) Pathologic features of fatal shark attacks. *The American Journal of Forensic Medicine and Pathology* 21(3):225–229.

Byard, R. W., R. A. James, and J. D. Gilbert (2002) Diagnostic problems associated with cadaveric trauma from animal activity. *The American Journal of Forensic Medicine and Pathology* 23(3):238–244.

Byard, R. W., R. A. James, and K. J. Heath (2006) Recovery of human remains after shark attack. *The American Journal of Forensic Medicine and Pathology* 27(3):256–259.

Bytheway, J. A., and S. M. Pustilnik (2013) Determining postmortem interval using glycoproteinous adhesion deposits by *Balanus improvisus* on human skeletal and dental remains. *Journal of Forensic Sciences* 58(1):200–205.

Calcinai, B., F. Azzini, G. Bavestrello, L. Gaggero, and C. Cerrano (2007) Excavating rates and boring pattern of *Cliona albimarginata* (Porifera: Clionaidae) in different substrata. In *Porifera Research: Biodiversity, Innovation and Sustainability—2007* (Vol. 28), ed. M. Reis Custódio, pp. 203–210. Série Livros, Museu Nacional, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil.

Castles, A. C. (1995) *The Shark Arm Murders: The Thrilling True Story of a Tiger Shark and a Tattooed Arm*. Wakefield Press, Kent Town, Australia.

Clare, A. S., S. C. Ward, D. Rittschof, and K. M. Wilbur (1994) Growth increments of the barnacle *Balanus amphitrite amphitrite* Darwin (Cirripedia). *Journal of Crustacean Biology* 14(1):27–35.

Clifford, C. (2011) Bodies from Air France Crash Arrive in France. Electronic document, http://www.cnn.com/2011/WORLD/europe/06/16/france.bodies.arrive/index.html#:~:text=Paris%20(CNN)%20%2D%2D%20The%20ship,according%20to%20French%20police%20sources.&text=AF%20447%20crashed%20two%20years,Brazil%2C%20killing%20all%20on%20board, accessed 4 October 2020.

Clifton, K. B., J. Yan, J. J. Mecholsky, Jr., and R. L. Reep (2008) Material properties of manatee rib bone. *Journal of Zoology* 274(2):150–159.

Clua, E., P.-M. Bescond, and D. Reid (2014) Fatal attack by a juvenile tiger shark, *Galeocerdo cuvier*, on a kitesurfer in New Caledonia (South Pacific). *Journal of Forensic and Legal Medicine* 25:67–70.

Clua, E., and D. Reid (2013) Features and motivation of a fatal attack by a juvenile white shark, *Carcharodon carcharias*, on a young male surfer in New Caledonia (South Pacific). *Journal of Forensic and Legal Medicine* 20:551–554.

Clua, E., and B. Séret (2010) Unprovoked fatal shark attack in Lifou Island (Loyalty Islands, New Caledonia, South Pacific) by a great white shark, *Carcharodon carcharias. American Journal of Forensic Medicine and Pathology* 31:281–286.

Copeland, A. R. (1987) Suicide by drowning. *American Journal of Forensic Medicine and Pathology* 8(1):18–22.

Crisp, D. J. (1954) The breeding of *Balanus porcatus* (Da Costa) in the Irish Sea. *Journal of the Marine Biological Association of the UK* 33(2):473–496.

Crisp, D. J., and E. Bourget (1985) Growth in barnacles. *Advances in Marine Biology* 22:199–244.

D'Alonzo, S. S., S. J. Clinkinbeard, and E. J. Bartelink (2012) Fluvial transport of human remains in the Sacramento River, California. *Proceedings of the American Academy of Forensic Sciences* 18:408–409.

Dahlgren, T. G., H. Wiklund, B. Källstrom, T. Lundälv, C. R. Smith, and A. G. Glover (2006) A shallow-water whale-fall experiment in the north Atlantic. *Cahiers de Biologie Marine* 47(4):385–389.

Davies, D. J., G. M. Staff, W. R. Callender, and E. N. Powell (1990) Description of a quantitative approach to taphonomy and taphofacies analysis: All dead things are not created equal. In *Paleocommunity Temporal Dynamics: The Long-Term Development of Multispecies Assemblies* ed. by W. Miller, pp. 328–350. Paleontological Society Special Publication 5. University of Tennessee, Department of Geological Sciences, Knoxville, TN.

Davis, P. G. (1997) The bioerosion of bird bones. *International Journal of Osteoarchaeology* 7(4):388–401.

De Donno, A., C. P. Campobasso, V. Santoro, S. Leonardi, S. Tafuri, and F. Introna (2014) Bodies in sequestered and non-sequestered aquatic environments: A comparative taphonomic study using decompositional scoring system. *Science & Justice* 54(6):439–446.

DeBattista, R., T. J. U. Thompson, C. E. L. Thompson, and R. L. Gowland (2013) A comparison of surface features on submerged and non-submerged bone using scanning electron microscopy. *Journal of Forensic and Legal Medicine* 20(6):770–776.

Dennison, K. J., J. A. Kieser, J. S. Buckeridge, and P. J. Bishop (2004) Post mortem cohabitation-shell growth as a measure of elapsed time: A case report. *Forensic Science International* 139:249–254.

Dickinson, G. H., I. E. Vega, K. J. Wahl, B. Orihuela, V. Beyley, E. N. Rodriguez, R. K. Everett, J. Bonaventura, and D. Rittschof (2009) Barnacle cement: A polymerization model based on evolutionary concepts. *The Journal of Experimental Biology* 212:3499–3510.

Dickson, G. C., and R. T. M. Poulter (2010) Microbial marine deposition: Marine bacteria as an indicator of postmortem submersion interval. *Proceedings of the American Academy of Forensic Sciences* 16:361–362.

Dilen, D. R. (1984) The motion of floating and submerged objects in the Chattahoochee River, Atlanta, GA. *Journal of Forensic Sciences* 29(4):1027–1037.

Dodson, P. (1973) The significance of small bones in paleoecological interpretation. *Contributions to Geology, University of Wyoming* 12:15–19.

Donoghue, E. R., and G. C. Minnigerode (1977) Human body buoyancy: A study of 98 men. *Journal of Forensic Sciences* 22(3):573–579.

Dumser, T. K., and M. Türkay (2008) Postmortem changes of human bodies on the bathyal sea floor—Two cases of aircraft accidents above the open sea. *Journal of Forensic Sciences* 53(5):1049–1052.

Eaton, J. P., and C. A. Haas (2011) *Titanic: Triumph and Tragedy* (3rd ed.). Haynes, Sparkford, UK.

Ebbesmeyer, C. C., and W. D. Haglund (1994) Drift trajectories of a floating human body simulated in a hydraulic model of Puget Sound. *Journal of Forensic Sciences* 39(1):231–240.

Ebbesmeyer, C. C., and W. D. Haglund (2002) Floating remains on Pacific Northwest waters. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 219–240. CRC Press, Boca Raton, FL.

Ehret, D. J., B. J. MacFadden, and R. Salas-Gismondi (2009) Caught in the act: Trophic interactions between a 4-million-year-old white shark (*Carcharodon*) and mysticete whale from Peru. *Palaios* 24(5):329–333.

Ellingham, S. T. D., P. Perich, and M. Tidball-Binz (2017) The fate of human remains in a maritime context and feasibility for forensic humanitarian action to assist in their recovery and identification. *Forensic Science International* 279:229–234.

Evans, J. W. (1968) Growth rate of the rock-boring clam *Penitella penita* (Conrad 1837) in relation to hardness of rock and other factors. *Ecology* 49(4):619–628.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Fernández-Jalvo, Y., and P. Andrews (2016) *Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification*. Springer, Dordrecht.

Fiorillo, A. R. (1988) Taphonomy of Hazard Homestead Quarry (Ogallala Group), Hitchcock County, Nebraska. *Contributions in Geology* 26(2):57–97.

Foecke, T., L. Maa, M. A. Russell, D. L. Conlin, and L. E. Murphy (2010) Investigating archaeological site formation processes on the battleship USS *Arizona* using finite element analysis. *Journal of Archaeological Science* 37(5):1090–1101.

Fox, M. (2003) Turret excavation reveals insights into ship's sinking. *Cheesebox* 13:8–11.

Fujikura, K., Y. Fujiwara, and M. Kawato (2006) A new species of *Osedax* (Annelida: Siboglinidae) associated with whale carcasses off Kyushu, Japan. *Zoological Science* 23(8):733–740.

García-Morato, S., M. D. Marin-Monfort, and Y. Fernández-Jalvo (2019) Rolling bones: A preliminary study of micromammal abrasion on different initial taphonomic stages. *Palaeontologia Electronica* 22(2):1–16.

Giertsen, J. C., and I. Morild (1989) Seafaring bodies. *American Journal of Forensic Medicine and Pathology* 10(1):25–27.

Gilbert, R. (1984) The movement of gravel by the alga *Fucus vesiculosus* (L.) on an arctic intertidal flat. *Journal of Sedimentary Petrology* 54(2):463–468.

Glover, A. G., B. Källstrom, C. R. Smith, and T. G. Dahlgren (2005) World-wide whale worms? A new species of *Osedax* from the shallow north Atlantic. *Proceedings of the Royal Society B* 272:2587–2592.

Glover, A. G., K. M. Kemp, C. R. Smith, and T. G. Dahlgren (2008) On the role of bone-eating worms in the degradation of marine vertebrate remains. *Proceedings of the Royal Society B* 275:1959–1961.

Goffredi, S. K., C. Paull, K. Fulton-Bennett, L. Hurtado, and R. Vrijenhoek (2004) Unusual benthic fauna associated with a whale fall in Monterey Canyon, California. *Deep-Sea Research Part I* 51:1295–1306.

Green, J. (2004) *Maritime Archaeology: A Technical Handbook* (2nd ed.). Elsevier, San Diego, CA.

Griffith, S. J. (2017) *Aquatic Bone Taphonomy: Forensic and Archaeological Implications for the Interpretation of Submerged Bone.* Ph.D. Dissertation, University of Southampton, Southampton, UK.

Griffith, S. J., C. E. L. Thompson, T. J. U. Thompson, R. L. Gowland (2016) Experimental abrasion of water submerged bone: The influence of bombardment by different sediment classes on microabrasion rate. *Journal of Archaeological Science: Reports* 10:15–29.

Gümrükçü, M. (2017) *Assessing the Effects of Fluvial Abrasion on Bone Surface Modifications Using High-Resolution 3-D Scanning.* M.A. Thesis, Colorado State University, Fort Collins, CO.

Gümrükçü, M., and M. C. Pante (2018) Assessing the effects of fluvial abrasion on bone surface modifications using high-resolution 3-D scanning. *Journal of Archaeological Science: Reports* 21:208–221.

Haglund, W. D. (1993) Disappearance of soft tissue and the disarticulation of human remains from aqueous environments. *Journal of Forensic Sciences* 38(4):806–815.

Haglund, W. D., and M. H. Sorg (2002) Human remains in water environments. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 201–218. CRC Press, Boca Raton, FL.

Hamilton, D. L. (1997) *Basic Methods of Conserving Underwater Archaeological Material Culture*. Legacy Resource Management Program, U.S. Department of Defense, Washington, DC.

Hamilton, D. L. (1999/2001) Conservation of cultural materials from underwater sites. *Archives and Museum Informatics* 13:291–323.

Hamilton, D. L. (2010) *Methods of Conserving Underwater Archaeological Material Culture* (rev. 2). Nautical Archaeology Program, Texas A&M University, College Station, TX.

Haszprunar, G. (1988) Anatomy and relationships of the bone-feeding limpets, *Cocculinella minutissima* (Smith) and *Osteopelta mirabilis* (Marshall) (Archaeogastropoda). *Journal of Molluscan Studies* 54(1):1–20.

Heaton, V., A. Lagden, C. Moffatt, and T. Simmons (2010) Predicting the postmortem submersion interval for human remains recovered from U.K. waterways. *Journal of Forensic Sciences* 55(2):302–307.

Higgs, N. D., A. G. Glover, T. G. Dahlgren, and C. T. S. Little (2010) Using computed-tomography to document borings by *Osedax mucofloris* in whale bone. *Cahiers de Biologie Marine* 51(4):401–405.

Higgs, N. D., A. G. Glover, T. G. Dahlgren, and C. T. S. Little (2011b) Bone-boring worms: Characterizing the morphology, rate, and method of bioerosion by *Osedax mucofloris* (Annelida, Siboglinidae). *Biological Bulletin, Marine Biological Laboratory, Woods Hole* 221:307–316.

Higgs, N. D., C. T. S. Little, and A. G. Glover (2011a) Bones as biofuel: A review of whale bone composition with implications for deep-sea biology and palaeoanthropology. *Proceedings of the Royal Society B* 278:9–17.

Higgs, N. D., C. T. S. Little, A. G. Glover, T. G. Dahlgren, C. R. Smith, and S. Dominici (2012) Evidence of *Osedax* worm borings in Pliocene (~3 Ma) whale bone from the Mediterranean. *Historical Biology* 24(3):269–277.

Hight, L. M., and J. J. Wilker (2007) Synergistic effects of metals and oxidants in the curing of marine mussel adhesive. *Journal of Material Science* 42(21):8934–8942.

Hoyoux, C., M. Zbinden, S. Samadi, F. Gaill, and P. Compère (2012) Diet and gut microorganisms of *Munidopsis* squat lobsters associated with natural woods and mesh-enclosed substrates in the deep South Pacific. *Marine Biology Research* 8(1):28–47.

Ihama, Y., K. Ninomiya, M. Noguchi, C. Fuke, and T. Miyazaki (2009) Characteristic features of injuries due to shark attacks: A review of 12 cases. *Legal Medicine* 11(5):219–225.

International Shark Attack File (2021) (Home page.) Electronic document, https://www.floridamuseum.ufl.edu/shark-attacks/, accessed 14 March 2021.

Introna, F., G. Di Vella, and C. P. Campobasso (2013) Migrant deaths and the *Kater Radez* I wreck: From recovery of the relict to marine taphonomic findings and identification of the victims. *International Journal of Legal Medicine* 127(4):871–879.

Irmis, R. B., and D. K. Elliot (2006) Taphonomy of a Middle Pennsylvanian marine vertebrate assemblage and an actualistic model for marine abrasion of teeth. *Palaios* 21(5):466–479.

İşcan, M. Y., and B. Q. McCabe (1995) Analysis of human remains recovered from a shark. *Forensic Science International* 72:15–23.

Johnson, S. B., A. Warén, R. W. Lee, Y. Kano, A. Kaim, A. Davis, E. E. Strong, and R. C. Vrijenhoek (2010) *Rubyspira*, new genus and two new species of bone-eating deep-sea snails with ancient habits. *Biological Bulletin* 219(2):166–167.

Jones, E. G., M. A. Collins, P. M. Bagley, D. Addison, and I. G. Priede (1998) The fate of cetacean carcasses in the deep sea: Observations on consumption rates and succession of scavenging species in the abyssal north-east Atlantic Ocean. *Proceedings of the Royal Society of London, B* 265:1119–1127.

Jones, W. J., S. B. Johnson, G. W. Rouse, and R. C. Vrijenhoek (2008) Marine worms (genus *Osedax*) colonize cow bones. *Proceedings of the Royal Society of London B* 275:387–391.

Jublier, N. and E. E. Clua (2018) Size assessment of the gray reef shark *Carcharhinus amblyrhynchos* inferred from teeth marks on human wounds. *Journal of Forensic Sciences* 63(5):1561–1567.

Kahana, T., J. Almog, J. Levy, E. Shmeltzer, Y. Spier, and J. Hiss (1999) Marine taphonomy: Adipocere formation in a series of bodies recovered from a single shipwreck. *Journal of Forensic Sciences* 44(5):897–901.

Kallal, R. J., S. J. Godfrey, and D. J. Ortner (2012) Bone reactions on a Pliocene cetacean rib indicate short-term survival of predation event. *International Journal of Osteoarchaeology* 22(3):253–260.

Kelly, S., and R. Bromley (1984) Ichnological nomenclature of clavate borings. *Palaeontology* 27(4):793–807.

LeBoeuf, B. J., M. Riedman, and R. S. Keyes (1982) White shark predation on pinnipeds in California coastal waters. *Fishery Bulletin* 80:891–895.

Lentz, A. K., G. H. Burgess, K. Perrin, J. A. Brown, D. W. Mozingo, and L. Lottenberg (2010) Mortality and management of 96 shark attacks and development of a shark bite severity scoring system. *The American Surgeon* 76(1):101–106.

Lewis, J. A., Jr., C. Y. Shiroma, K. Von Guenthner, and K. N. Dunn (2004) Recovery and identification of the victims of the *Ehime Maru*/USS *Greeneville* collision at sea. *Journal of Forensic Sciences* 49(3):539–542.

Liebig, P. M., K. W. Flessa, and T.-S. A. Taylor (2007) Taphonomic variation despite catastrophic mortality: Analysis of a mass stranding of false killer whales (*Pseudorca crassidens*), Gulf of California, Mexico. *Palaios* 22(4):384–391.

Liebig, P. M., T.-S. A. Taylor, and K. W. Flessa (2003) Bones on the beach: Marine mammal taphonomy of the Colorado Delta, Mexico. *Palaios* 18(2):168–175.

London, M. R., F. J. Krolikowski, and J. H. Davis (1997) Burials at sea. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 615–622. CRC Press, Boca Raton, FL.

Lough, J. M., and T. F. Cooper (2011) New insights from coral growth band studies in an era of rapid environmental change. *Earth-Science Reviews* 108(3–4):170–184.

Love, A. C. (2002) Darwin and *Cirripedia* prior to 1846: Exploring the origins of the barnacle research. *Journal of the History of Biology* 35(2):251–289.

Lowry, D., A. L. F. de Castro, K. Mara, L. B. Whitenack, B. Delius, G. H. Burgess, and P. Motta (2009) Determining shark size from forensic analysis of bite damage. *Marine Biology* 156(12):2483–2492.

Lucas, Z., and W. T. Stobo (2000) Shark-inflicted mortality on a population of harbor seals (*Phoca vitulina*) at Sable Island, Nova Scotia. *Journal of Zoology, London* 252:405–414.

Lundsten, L., K. L. Schlining, K. Frasier, S. B. Johnson, L. Kuhnz, J. B. J. Harvey, G. Clague, and R. C. Vrijenhoek (2010) Time-series analysis of six whale-fall communities in Monterey Canyon, California, USA. *Deep-Sea Research I* 57(12):1573–1584.

Madgwick, R. (2014) What makes bones shiny? Investigating trampling as a cause of bone abrasion. *Archaeological and Anthropological Sciences* 6(2):163–173.

Makino, Y., K. Tachihara, S. Ageda, T. Arao, C. Fuke, and T. Miyazaki (2004) Peculiar circular and C-shaped injuries on a body from the sea. *American Journal of Forensic Medicine and Pathology* 25(2):169–171.

Marshall, B. A. (1987) Osteopeltidae (Mollusca: Gastropoda): A new family of limpets associated with whale bone in the deep sea. *Journal of Molluscan Studies* 53(2):121–127.

Martin, R. A., D. K. Rossmo, and N. Hammerschlag (2009) Hunting patterns and geographic profiling of white shark predation. *Journal of Zoology* 279:111–118.

Mateus, M., and V. Vieira (2014) Study on the postmortem submersion interval and accumulated degree days for a multiple drowning accident. *Forensic Science International* 238:e15–e19.

Mégnin, J. P. (1894) *La Faune des Cadavres Application de l'Entomologie à la Médecine Légale*. G. Masson, Paris.

Megyesi, M. S., S. P. Nawrocki, and N. H. Haskell (2005) Using Accumulated Degree-Days to estimate the postmortem interval from decomposed human remains. *Journal of Forensic Sciences* 50(3):618–626.

Nakaya, K. (1993) A fatal attack by a white shark in Japan and a review of shark attacks in Japanese waters. *Japanese Journal of Ichthyology* 40(1):35–42.

Nambiar, P., T. E. Bridges, and K. A. Brown (1991) Allometric relationships of the dentition of the great white shark, *Carcharodon carcharias*, in forensic investigations of shark attacks. *Journal of Forensic Odonto-Stomatology* 9(1):1–16.

Nambiar, P., K. A. Brown, and T. E. Bridges (1996) Forensic implications of the variation in morphology of marginal serrations on the teeth of the great white shark. *Journal of Forensic Odonto-Stomatology* 14(1):3–9.

Nasti, A. (2017) A taphonomic approach to marine abrasion on human bones. *Forensic Research and Criminology International Journal* 5(3):00154.

National Oceanic and Atmospheric Administration (2017) National Marine Sanctuaries. The 2010 Scientific Expedition to *Titanic*. Electronic document, https://sanctuaries.noaa.gov/maritime/titanic/2010_expedition.html, accessed 14 March 2021.

National Park Service (2020) [Cape Cod] Shipwrecks. Electronic document, https://www.nps.gov/caco/learn/historyculture/shipwrecks.htm, accessed 14 March 2021.

Nawrocki, S. P., J. E. Pless, D. A. Hawley, and S. A. Wagner (1997) Fluvial transport of human crania. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 529–552. CRC Press, Boca Raton, FL.

O'Brien, T. G., and A. C. Kuehner (2007) Waxing grave about adipocere: Soft tissue change in an aquatic context. *Journal of Forensic Sciences* 52(2):294–301.

Palmer, C. (2020) Estimating the impact of laminar flow on the pattern and rate of decomposition in aquatic environments—Is there a better way of modeling decomposition? *Journal of Forensic Sciences* 65(5):1601–1609.

Papastamatiou, Y. P., S. J. Purkis, and K. N. Holland (2007) The response of gastric pH and motility to fasting and feeding in free swimming blacktip reef sharks, *Carcharhinus melanopterus*. *Journal of Experimental Marine Biology and Ecology* 345:129–140.

Parsons, K. M., and C. E. Brett (1991) Taphonomic processes and biases in modern marine environments: An actualistic perspective on fossil assemblage preservation. In *The Processes of Fossilization* ed. by S. K. Donovan, pp. 22–65. Columbia University Press, New York.

Payne, J. A. (1965) A summer carrion study of the baby pig, *Sus scrofa* Linnaeus. *Ecology* 46(5):592–602.

Payne, J. A., and E. W. King (1972) Insect succession and decomposition of pig carcasses in water. *Journal of the Georgia Entomological Society* 7(3):153–162.

Pokines, J. T., C. J. Eck, and M. E. Sharpe (2017) Sources of skeletal remains at a chief medical examiner's office: Who finds the bones? *Journal of Forensic Identification* 67(2):278–299.

Pokines, J. T., and N. Higgs (2015) Macroscopic taphonomic alterations to human bone in marine environments. *Journal of Forensic Identification* 65(6):953–984.

Pokines, J. T., M. Menschel, S. Mills, E. Janowiak, R. Satish, C. Kincer, and S. Soltani (2020) Experimental formation of marine abrasion on bone and the forensic postmortem interval. *Forensic Anthropology* 3(4):175–189.

Pomponi, S. A. (1980) Cytological mechanisms of calcium carbonate excavation by boring sponges. *International Review of Cytology* 65:301–319.

Prassack, K. A. (2011) The effect of weathering on bird bone survivorship in modern and fossil saline-alkaline lake environments. *Paleobiology* 37(4):633–654.

Purcell, M., S. Pascaud, D. Gallo, M. Rothenbeck, M. Dennett, G. Packard, and A. Sherrell (2011) Use of REMUS 6000 AUVs in the search for the Air France Flight 447. *Proceedings of the IEEE Oceans 2011 Conference*, Hilo, HI, September 19–22, 2011.

Pyenson, N. D. (2010) Carcasses on the coastline: Measuring the ecological fidelity of the cetacean stranding record in the eastern North Pacific Ocean. *Paleobiology* 36(3):453–480.

Rasher, D. B., S. Engel, V. Bonito, G. J. Fraser, J. P. Montoya, and M. E. Hay (2012) Effects of herbivory, nutrients, and reef protection on algal proliferation and coral growth on a tropical reef. *Oecologia* 169:187–198.

Rathbun, T. A., and B. C. Rathbun (1997) Human remains recovered from a shark's stomach in South Carolina. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 449–456. CRC Press, Boca Raton, FL.

Raymer, E. C. (1996) *Descent into Darkness; Pearl Harbor, 1941: The True Story of a Navy Diver.* Presidio Press, Novato, CA.

Ribéreau-Gayon, A., D. O. Carter, and S. Regan (2018) New evidence of predation on humans by cookiecutter sharks in Kauai, Hawaii. *International Journal of Legal Medicine* 132(5):1381–1387.

Ritter, E. K., and M. L. Levine (2005) Bite motivation of sharks reflected by the wound structure on humans. *American Journal of Forensic Medicine and Pathology* 26(2):136–140.

Rouse, G. W., S. K. Goffredi, S. B. Johnson, and R. C. Vrijenhoek (2011) Not whale-fall specialists, *Osedax* worms also consume fishbones. *Biology Letters* 7(5):736–739.

Rouse, G. W., S. K. Goffredi, and R. C. Vrijenhoek (2004) *Osedax*: Bone-eating marine worms with dwarf males. *Science* 305(5684):668–671.

Rouse, G. W., N. G. Wilson, S. K. Goffredi, S. B. Johnson, T. Smart, C. Widmer, C. M. Young, and R. C. Vrijenhoek (2009) Spawning and development in *Osedax* boneworms (Siboglinidae, Annelida). *Marine Biology* 156(3):395–405.

Rouse, G. W., K. Worsaae, S. B. Johnson, W. J. Jones, and R. C. Vrijenhoek (2008) Acquisition of dwarf male 'harems' by recently settled females of *Osedax roseus* n. sp. (Siboglinidae; Annelida). *Biological Bulletin* 214(1):67–82.

Rtshiladze, M. A., S. P. Andersen, D. Q. A. Nguyen, A. Grabs, and K. Ho (2011) The 2009 Sydney shark attacks: Case series and literature review. *ANZ Journal of Surgery* 81(5):345–351.

Savazzi, E. (1999) Boring, nestling and tube-dwelling bivalves. In *Functional Morphology of the Invertebrate Skeleton* ed. E. Savazzi, pp. 205–237. Wiley, Chichester, UK.

Schoenen, D., and H. Schoenen (2013) Adipocere formation—The result of insufficient microbial degradation. *Forensic Science International* 226:301.e1–301.e6.

Shipman, P., and J. J. Rose (1988) Bone tools: An experimental approach. In *Scanning Electron Microscopy in Archaeology* ed. by S. L. Olsen, pp. 303–335. British Archaeological Reports, International Series 452, Oxford.

Skinner, M. F., J. Duffy, and D. B. Symes (1988) Repeat identification of skeletonized human remains: A case study. *Journal of the Canadian Society of Forensic Science* 21(3):138–141.

Smith, A. M. (2002) The structure and function of adhesive gels from invertebrates. *Integrative and Comparative Biology* 42(6):1164–1171.

Smith, C. R., and A. Baco (2003) Ecology of whale falls at the deep-sea floor. *Oceanography and Marine Biology: An Annual Review* 41:311–354.

Sorg, M. H., J. H. Dearborn, E. I. Monahan, H. F. Ryan, K. G. Sweeney, and E. David (1997) Forensic taphonomy in marine contexts. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. W. D. Haglund and M. H. Sorg, pp. 567–604. CRC Press, Boca Raton, FL.

Steneck, R. S. (1986) The ecology of coralline algal crusts: Convergent patterns and adaptative strategies. *Annual Review of Ecology and Systematics* 17(1):273–303.

Steptoe, D. P., and W. B. Wood (2002) The human remains from HMS *Pandora*. *Internet Archaeology* 11. DOI: 10.11141/ia.11.4.

Stewart, R. J., T. C. Ransom, and V. Hlady (2011) Natural underwater adhesives. *Polymer Physics* 49(11):757–771.

Stirland, A. J. (2005) *The Men of the Mary Rose: Raising the Dead* (rev. ed.). Sutton Publishing, Phoenix Mill, UK.

Stock, M. K., A. P. Winburn, and G. H. Burgess (2017) Skeletal indicators of shark feeding on human remains: Evidence from Florida forensic anthropology cases. *Journal of Forensic Sciences* 62(6):1647–1654.

Stojanowski, C. M. (2002) Hydrodynamic sorting in a coastal marine skeletal assemblage. *International Journal of Osteoarchaeology* 12(4):259–278.

Tapanila, L., E. M. Roberts, M. L. Bouaré, F. Sissoko, and M. A. O'Leary (2004) Bivalve borings in phosphatic coprolites and bone, Cretaceous-Paleogene, northeastern Mali. *Palaios* 19(6):565–573.

Thompson, C. E., L. S. Ball, T. J. U. Thompson, and R. Gowland (2013) The abrasion of modern and archaeological bones by mobile sediments: The importance of transport modes. *Journal of Archaeological Science* 38(4):784–793.

Trueman, C., and D. M. Martill (2002) The long-term survival of bone: The role of bioerosion. *Archaeometry* 44(3):371–382.

Ubelaker, D. H., and K. M. Zarenko (2011) Adipocere: What is known after over two centuries of research. *Forensic Science International* 208:167–172.

van Daalen, M. A., D. S. de Kat, B. F. L. Oude Grotebevelsborg, R. de Leeuwe, J. Warnaar, R. J. Oostra, and W. L. J. M. Duijst-Heesters (2017) An aquatic decomposition scoring method to potentially predict the postmortem submersion interval of bodies recovered from the North Sea. *Journal of Forensic Sciences* 62(2):369–373.

Voorhies, M. R. (1969) Taphonomy and population dynamics of an Early Pliocene vertebrate fauna, Knox County, Nebraska. *University of Wyoming, Contributions to Geology*, Laramie, WY, Special Paper No. 1.

Vrijenhoek, R. C., S. Johnson, and G. W. Rouse (2009) A remarkable diversity of bone-eating worms (*Osedax*; Siboglinidae; Annelida). *BMC Biology* 7:74. DOI: 10.1186/1741-7007-7-74.

Vullo, R. (2009) Taphonomy of vertebrate microfossil assemblages in coastal environments: In search of a modern analogous model. *Palaios* 24(11):723–725.

Waite, J. H. (2002) Adhesion à la moule. *Integrative and Comparative Biology* 42(6):1172–1180.

Warén, A. (2011) Molluscs on biogenic substrates. In *The Natural History of Santo* ed. by P. Bouchet, H. Le Guyader, and O. Pascal, pp. 438–448. MNHN, Paris; IRD, Marseille; PNI, Paris.

Weigelt, J. (1989 [1927]) *Recent Vertebrate Carcasses and Their Paleobiological Implications*. Reprint edition, translated by J. Schaefer. University of Chicago Press, Chicago.

West, J. G. (2011) Changing patterns of shark attacks in Australian waters. *Marine and Freshwater Research* 62(6):744–754.

Westling, L. (2012) *Underwater Decomposition: An Examination of Factors Surrounding Freshwater Decomposition in Eastern Massachusetts*. M.S. Thesis, Boston University School of Medicine, Boston, MA.

White, J. A., G. H. Burgess, M. Nakatsukasa, M. J. Hudson, J. Pouncett, S. Kusaka, M. Yoneda, Y. Yamada, and R. J. Schulting (2021) 3000-year-old shark attack victim from Tsukumo shellmound, Okayama, Japan. *Journal of Archaeological Science: Reports* 38:103065. DOI: 10.1016/j.jasrep.2021.103065.

Whitenack, L. B., and P. J. Motta (2010) Performance of shark teeth during puncture and draw: Implications for the mechanics of cutting. *Biological Journal of the Linnean Society* 100(2):271–286.

Wroe, S., D. R. Huber, M. Lowry, C. McHenry, K. Moreno, P. Clausen, T. L. Ferrara, E. Cunningham, M. N. Dean, and A. P. Summers (2008) Three-dimensional computer analysis of white shark jaw mechanics: How hard can a great white bite? *Journal of Zoology, London* 276:336–342.

Yoshino, M., T. Kimijima, S. Miyasaka, H. Sato, and S. Seta (1991) Microscopical study on estimation of time since death in skeletal remains. *Forensic Science International* 49:143–158.

Zimmerman, K. A., and J. R. Wallace (2008) The potential to determine a postmortem submersion interval based on algal/diatom diversity on decomposing mammalian carcasses in brackish ponds in Delaware. *Journal of Forensic Sciences* 53(4):935–941.

Contemporary Cultural Alterations to Bone

Anatomical, Ritual, and Trophy

8

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Contents

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> A cast of your skull, sir, until the original is available, would be an ornament to any anthropological museum. It is not my intention to be fulsome, but I confess that I covet your skull.
>
> **—Sir Arthur Conan Doyle,**
> *The Hound of the Baskervilles*

Introduction

Some of the most prevalent taphonomic features observed on human skeletal remains are derived from contemporary cultural contexts in the USA: anatomical teaching, ritual, and trophy display. These remains have in common their manipulation and alteration in recent contexts and their ubiquitous appearance as cases requiring examination in medical examiner and other forensic laboratory settings (Bass 1983; Pokines 2015a, 2018, 2020; Sledzik and Ousley 1991; Taylor et al. 1984; Wienker et al. 1990; Willey and Leach 2009; Yucha et al. 2017). They also tend to overlap in multiple taphonomic characteristics due to frequent common origins as remains pillaged from cemetery contexts (see Chapter 5, this volume) or culled from teaching collections and repurposed for display.

A review of the cultural practices affecting human skeletal remains throughout history and prehistory would be the work of several volumes. Since the Lower Paleolithic period, osseous tissues (bones, teeth/ivory, and antler) have been a frequently used material in tool manufacture (Backwell and d'Errico 2003; Bonnichsen and Sorg 1989; Brain 1981; Lesnik 2011; Morlan 1984) due to their relative ease of shaping combined with their durability and flexibility (MacGregor 1985). Human bone also has been used as a frequent cross-cultural venue for artistic expression, both as a relatively innocuous raw material and as a cultural signifier themselves when their original morphology is deliberately retained. Skull motifs (whether signifying rebellion, intimidation, death, or sciences involving osteology, for example) are commonly seen on clothing, personal items, and tattoos, and retain a general acceptance in contemporary US society.

The display and handling of actual human skulls, however, is less accepted by the public and is more confined to specific subcultural segments (Nafte 2014). Such human remains tend to be anatomical teaching, personal display specimens, or ritual objects used in contemporary religions and cults. *Anatomical remains* are processed bones used in medical, teaching, or research facilities, and these often find their way into the hands of the public or are discarded in contexts requiring their later forensic examination. These have many taphonomic characteristics in common with *ritual remains* (many of which originally derived from anatomical teaching specimens). Human remains used in ritual or ceremonial practices also may derive from cemetery contexts and be modified for religious purposes, such as in some Afro-Caribbean cultures (Winburn et al. 2016, 2017). An additional type is termed *trophy remains*, the body part souvenir from a vanquished enemy (Yucha et al. 2017). As discussed below ("Trophy Remains" section), this type of behavior occurred frequently during the mechanized warfare of the twentieth century in the Pacific, and human remains from this source still find their way to forensic anthropological examination in the USA.

Anatomical Remains

History of Anatomical Remains

Despite cultural stigmas, human remains have been used for dissection and medical/anatomical education as early as the third century BC by the Greeks (Walker 2008). Widespread documented use of human cadavers for medical purposes in Western cultures, however, did not occur until the Renaissance period (fourteenth to seventeenth centuries AD). During this time, religious stigmatization decreased, and the value of human remains for scientific research and medical education began to be realized (Walker 2008). Blakely and Harrington (1997:165) noted that the "clash between beliefs about death—both medical and religious—and the needs of the medical profession reached a zenith in the eighteenth and nineteenth centuries". Evidence of autopsy in the New World dates to as early as 1604 (Crist and Sorg 2016). By the eighteenth century, the utilization and demand for human cadavers increased significantly. In Europe, medical students were required to learn human anatomy and to have hands-on practice with cadavers. Similarly, to become a licensed doctor in the USA, an individual was required to have practical experience in anatomical dissection, but both dissection and the possession of cadavers were largely illegal at that time, thereby creating a logical conundrum (Iserson 2001).

Also at that time, many countries lacked legal venues for human body acquisition to meet the increased demands of medical schools (Iserson 2001; Richardson 2000; Sappol 2002). Laws were created to satisfy the shortage, yet religious stigmas and ethnocentric belief systems influenced the acquisition and sources of human cadavers during this period. In 1752, the English Parliament enacted the Murder Act, whereby the bodies of convicted murderers were prohibited from being buried, and public dissection following execution was mandated (Halperin 2007). Throughout both Europe and North America, adult anatomical specimens began to be legally procured from people who died because of duels, executed criminals, prison inmates who died naturally, and the unclaimed corpses of the poor, while the remains of children came from orphans, stillbirths, or unbaptized infants, usually of the poor. The supply of legal remains proved insufficient, and medical schools soon began the opportunistic procurement of cadavers from relatives of those teaching, body snatching or grave robbing, and in extreme cases from people murdered for the use of their bodies (Halperin 2007; Roach 2003).

In the USA, the majority of remains for anatomical dissection were acquired from disenfranchised groups that could neither object nor prevent their dead from being stolen, namely, the poor, the mentally and physically disabled, criminals, immigrants, and African Americans (Blakely and Harrington 1997; Halperin 2007; Hildebrandt 2008; Jones and Whitaker 2012; Stubblefield 2011), which continues in some parts of the world today (Anyanwu et al. 2011). Laws were enacted to make grave robbing and the opportunistic acquisition of human remains a crime in both Europe and the USA, beginning with New York in 1789 (Blake 1955). The Warburton Act (or Anatomy Act) of 1832, passed by the UK Parliament, required individuals who practiced anatomy to have a license and to report the source of their cadavers. State governments in the USA began to enact similar laws concerning the legal acquisition of cadavers beginning in 1831 with Massachusetts (Blake 1955). The US anatomy laws were passed only on a state-by-state basis, so there was no national uniformity (Humphrey 1973; Iserson 2001).

During this period, skeletons used for teaching specimens were frequently "leftovers" from anatomical dissections. In the modern era (from the mid-1960s to present), most remains used for anatomical dissections are acquired from individuals who have willed or actively donated their remains to science. In most of these instances, virtually all the tissue is either cremated or returned for burial depending on the individual's or family's wishes following dissection. Because of this, skeletal material used for teaching in the modern era usually is purchased after the soft tissue has been removed and is not acquired from dissections.

During recent history, India was the primary source of anatomical material (Hefner et al. 2016; Stubblefield 2011). Much of the demand for cadavers and skeletons from India grew from the need in England for medical school specimens, which decreased after Indian independence in 1947, but demand from the USA grew after that time (Carney 2007). During the twentieth century, major sources of anatomical specimens in the USA were those purchased and acquired from India and Bangladesh prior to the 1985 ban on the export of human material from those countries (Carney 2007; Fineman 1991; Hefner et al. 2016; Pokines et al. 2017; Schultz 2012). Much of the skeletal export market then shifted to China, which subsequently banned export in 2006 (Cumback 2018; Marsh 2012). Black market exports, however, persist (Carney 2007). Today, human skeletal remains can be purchased from several US biological supply companies for which the source material originated from India, after refurbishing older remains (Bernstein 2018; Skulls Unlimited International 2021; The Bone Room 2019). While the major internet retailers eBay and Etsy have banned the sale of human remains (Cumback 2018), prior to this they had a thriving market of all types of skeletal remains (Huffer and Chappell 2014; Hugo 2016; Huxley and Finnegan 2004; Seidemann et al. 2009). Anatomically prepared human remains still can be purchased from private sellers (B for Bones 2018; Hong Kong Blue Bay 2021; Meiwo Science 2015; Osta International 2019; Skull Store 2021; Skulls Unlimited International 2021; The Bone Room 2019; Young Brothers 2021). In the case of most, if not all, of these sources of human anatomical remains, the provenience and demographic information is lacking.

Collectors of human remains, including medical professionals and laypersons, often display the skeletal material as curiosities, typically skulls having visible medical anomalies such as pathological conditions, trauma, and other interesting cases (Davis 2015; Redman 2016; Walker 2008). Human skeletal remains were often preserved for extended display as anatomical art for public viewing (Hansen 1996) or as art alone (Nafte 2014). Many of these collections were preserved and appropriated to either museums or educational facilities. Disposal of unwanted anatomical specimens prior to the 1970s was an "informal process" that often resulted in interment at a waste site (Stubblefield 2011). Skeletons of dissected cadavers can undergo extensive sectioning and other cutting, sometimes as practice for surgical procedures (Davidson 2007; Hodge 2013; Mann et al. 1991; McFarlin and Wineski 1997; Owsley 1995; Scovil 2015). These remains were sometimes informally discarded at the source and have been excavated from the locations of former anatomical teaching facilities (Hodge 2013; Mann et al. 1991; McFarlin and Wineski 1997; Mitchell 2012; Nystrom 2017; Willey et al. in press). Their taphonomic effects should combine evidence of sharp force trauma (usually saw cuts but also some drilling) overlapped by burial effects (Chapter 5).

In other instances, disposal of anatomical display skulls is the responsibility of relatives of a deceased previous owner, after they inadvertently found human remains among the deceased person's belongings. Since disposal often involves haphazard discard leading to later discovery, contact with law enforcement and the involvement of forensic anthropologists often follows. Once separated from their original contexts, former anatomical teaching specimens may end up with law enforcement officials through multiple means, including seizure from a residence, seizure from a public sale, or voluntary turnover to police (Pokines 2015a; Pokines et al. 2017). The latter category can include remains formerly in the direct possession of a previous anatomical student, teacher (including medical doctors), or teaching institution that no longer has use for them. Some remains also are abandoned or have been repurposed in a visible manner. Analysis, however, should treat the suspected origin of these remains as a hypothesis to be tested (Pokines 2018), with accompanying statements regarding their origin as only one consideration, and a full analysis should be completed that includes recording all taphonomic effects (Chapter 21).

The legality of ownership of human skeletal remains in the USA is complicated and may lead to some specimens being forwarded to law enforcement out of uncertainty about the applicable laws (Pokines et al. 2017). The Native American Graves Protection and Repatriation Act (NAGPRA) of 1990 regulates the possession of Native American remains on a federal level (Seidemann 2004, 2010), but most laws and their enforcement regarding the buying and selling of human remains are at the state level (Hutt and Riddle 2007; Seidemann 2010). These can vary significantly: 38 states have laws regarding the buying and selling of human remains (Halling and Seidemann 2016). Sixteen states prohibit the possession of human remains, but four of these apply only to Native American remains (Halling and Seidemann 2016). Louisiana made it illegal to possess, trade in, discard, or destroy human remains except as otherwise permitted by law; exceptions include teaching institutions and museums (Louisiana State Senate 2016). New York, Georgia, and Tennessee are the only ones to ban the trade of human remains across state lines (Hugo 2016), and some retailers specifically note that they will not ship to these states (e.g., The Bone Room 2019). While it is feasible to monitor established sellers for the legality of their transactions, there is less ability to monitor the purchasers (Halling and Seidemann 2016; Hugo 2016), and private sales by antique dealers or other individuals may go unnoticed.

Taphonomic Characteristics of Anatomical Remains

The observed common taphonomic features have been categorized according to three sets of criteria relating to (1) original preparation, (2) features from display and use for anatomical teaching, or (3) features related to subsequent curation and storage of the remains. Additional features may arise from their subsequent repurposing as display items, whether more informally or as a part of ritual use. The data presented on taphonomic effects derive from a study by Pokines (2015a) on former anatomical cases received at the Office of the Chief Medical Examiner (OCME), Boston, Massachusetts, USA, and were supplemented with new data (total n = 34) tabulated from the same source (Table 8.1). For supplemental information on how their origins affect their taphonomic characteristics, Pokines et al. (2017) examined a sample (n = 84) of anatomical teaching skulls (Table 8.2) that were still in heavy use at the Boston University School of Medicine (BUSM). Remains deriving from sources similar to the latter sample must have at some time in the past contributed to the influx of anatomical specimens needing forensic anthropological analysis.

Commingling: The OCME sample derived from a total of 26 cases received, which were subdivided into 34 individual cases where distinct individuals were recognized, usually due to the presence of multiple crania. Two cases included commingled postcranial elements that could not be separated, and both had a minimum number of individuals (MNI) of three. All the BUSM cases included at a minimum a mandible and sectioned

Table 8.1 **Taphonomic Characteristics from Anatomical Preparation, Forensic Sample (n = 34) from the Office of the Chief Medical Examiner (OCME) Massachusetts, USA**

Characteristic(s)	n =	%	Comments
		Original Skeletal Preparation	
Striations	2	5.9	From scrubbing
Bleaching	7	20.6	From maceration
Orange Maceration Staining	2	5.9	Possibly associated with bleaching chemicals (see Chapter 12)
Mineral staining ($CaCO_3$)	1	2.9	From maceration
		Display and Use Preparation	
Hardware	18	52.9	
Fe or Cu staining	4	11.8	Associated with steel or brass mounting hardware
Suspension hole	5	20.8	% of cases with superior cranial vault intact (5 of 24)
Other drilling	19	55.9	
Sectioning	11	32.4	
Other cutting	5	14.7	
Plastic reconstruction	6	17.7	
Labeling	6	17.7	
Coating	4	11.8	
		Curation	
Patina	20	58.8	
Color change			
None	21	61.8	Retained bleaching from initial processing or original natural bone color
Medium brown	8	23.5	
Dark brown/gray	5	14.7	
Ink and Pencil Marks	16	47.1	
Shelf wear	8	33.3	% of cases with inferior cranial portions (8 of 24)
Other breakage	32	94.1	
Taping	2	5.9	
Gluing	11	32.4	
Bone condition			
Organic sheen	28	82.4	
Chalky/friable	5	14.7	
Localized chalky/friable	1	2.9	Affected one complete mounted skeleton
Adhering particles	11	32.4	7 dust (20.6%), 3 sediment (8.8%), 1 ashes (2.9%)
		Repurposing	
Thermal alteration	4	11.8	Likely from candles
Wax	7	20.6	Likely from candles
Paint	6	17.7	
Mineral staining	3	8.8	
Chopping marks	1	2.9	Enhancements to give an ordinary skull a purported battle origin

Source: Pokines (2015a) and new data; used with permission, *Journal of Forensic Identification*.

Table 8.2 **Taphonomic Alterations to a Sample (n = 84) of Anatomical Teaching Skulls from Boston University Medical School, USA**

Taphonomic Alteration	n =	%	Notes
Taphonomic Characteristics Related to Preparation for Display and Use			
Plastic teeth			
Maxilla	5	6.0	
Mandible	6	7.1	
Tooth staining	22	26.2	
Striations from scrubbing	2	2.4	
Bone color			
Normal (unbleached)	71	84.5	
Some bleaching	13	15.5	
Bone condition			
Organic sheen	80	95.2	
Chalky	3	3.6	
Mixed	1	1.2	
Thermal alteration (scorching)	0	0.0	
Mineral staining ($CaCO_3$)	46	54.8	
Orange maceration staining	16	19.0	
Black maceration staining	18	21.4	
Hardware			
Calotte pins (>1)	59	70.2	
Calotte pin holes only	16	19.0	
Mandible springs	58	69.0	
Mandible springs - posts only	7	8.3	
Mandible springs - holes only	6	7.1	
Spring posts on cranium	61	72.6	
Spring posts on cranium - holes only	4	4.8	
Calotte hooks + eyelets or posts	60	71.4	
Holes from hooks + eyelets or posts	6	7.1	
Calotte eyelets or posts only	2	2.4	
Wire on mandible	4	4.8	
Suspension hole	2	2.4	
Calotte sectioning			
Straight	80	95.2	
Irregular, curved, or angled	4	4.8	
Other cutting	3	3.6	
Other drilling	4	4.8	
Labeling			
Specimen # (one or more)	66	78.6	
Company	9	10.7	
Structures	14	16.7	
Coating	16	19.0	
Plastic reconstruction	21	25.0	
Taphonomic Characteristics Related to Curation			
Patina	62	73.8	
Ink marks	76	90.5	
Writing in ink	32	38.1	
Pencil marks	69	82.1	

(Continued)

Table 8.2 ***(Continued)*** **Taphonomic Alterations to a Sample (n = 84) of Anatomical Teaching Skulls from Boston University Medical School, USA**

Taphonomic Alteration	n =	%	Notes
Writing in pencil	24	28.6	
Paint	3	3.6	
Taping/residue	18	21.4	
Gluing			
Teeth	65	77.4	
Other	23	27.4	
Dust or sediment	16	19.0	
Dental wax	6	7.1	
Modeling clay	4	4.8	
Shelf wear			
Gonial	25	29.8	
Occipital condyles	43	51.2	
Mastoids	18	21.4	
Other	11	13.1	
Breakage			
Lacrimals	77	91.7	
Nasals	70	83.3	
Inferior nasal conchae	54	64.3	
Vomer	74	88.1	
Orbits	77	91.7	
Maxillae (non-alveolar)	2	2.4	
Zygomatics	2	2.4	
Endocranial portion	71	84.5	
Styloids	81	96.4	
Palatines	1	1.2	
Maxillary alveolar margins	64	76.2	
Mandible alveolar margins	58	69.0	
Mandible condyles	52	61.9	
Mandible other (non-alveolar)	11	13.1	
Vault	26	31.0	
Teeth	77	100.0	% (of n = 77) does not include fully antemortem/postmortem edentulous cases
Postmortem tooth loss	80	95.2	
Labeling tape	1	1.2	
“Zip tie”	2	2.4	
Pipe cleaner	2	2.4	
Mold	4	4.8	
Coffee stains	3	3.6	
Skeletal Representation			
Complete skull (calotte, cranium, mandible)	84	100.0	
MNI = 1	54	64.3	
MNI = 2	27	32.1	
MNI = 3	3	3.6	

Source: Pokines et al. (2017); used with permission, *Journal of Forensic Identification*.

cranium/calotte, but it was clear in some cases that these portions did not articulate. The MNI was either one (64.3%), two (32.1%), or three (3.6%).

Cultural: Many skeletons prepared as anatomical specimens came from India for many years (Hefner et al. 2016), and a common practice in that country is chewing of betel nut, a substance that causes tooth staining when practiced habitually. Tooth staining consistent with this source was present on nine (26.2%) of the BUSM sample but was not noted among the OCME sample.

Taphonomic Characteristics Related to Initial Preparation

Bleaching/Whitening: There are several methods used in modern times to *macerate* (remove soft tissue from) human skeletal remains, and a number of these techniques are employed in combination or sequentially and may leave recognizable alterations on the skeletal material (Chapter 12). Common methods of tissue removal include boiling or prolonged warm water submersion, often with the use of common laundry detergents, hydrogen peroxide (H_2O_2), or bleach (sodium hypochlorite, NaClO) (Fenton et al. 2003; Snyder et al. 1975; Stephens 1979). Boiling can be accompanied by manual scrubbing to remove adhering soft tissue and may leave behind characteristic micro-abrasions or other tool marks. Other methods of defleshing include consumption of dried tissue by dermestid beetles (*Dermestes maculatus*) and consumption of moist tissue by blowfly maggots (Calliphoridae) during outdoor decomposition, which may leave evidence of environmental exposure. In India, the likely source of many of the anatomical cases examined here, preparation can include maceration in tanks for up to six months, followed by washing the bones, soaking them in hydrogen peroxide, rinsing, then drying them in the sun. Maceration also can proceed by boiling followed by brief autoclaving of the bones in sodium hydroxide (Kamath et al. 2016). Varnish is also sometimes applied following initial preparation of the anatomical skeletal material in order to prevent flaking and damage to the bone (Snyder et al. 1975).

Bleaching was uncommon in the OCME sample, with only seven cases (20.6%) having detectible bleaching (Table 8.1). Striations consistent with repeated scrubbing also were rare, with only two cases (5.9%) having visible striations. No direct thermal alteration (scorching) from maceration was detected. Direct thermal alteration also was not seen in any of the BUSM cases examined, but mineral scale (likely mostly calcium carbonate [$CaCO_3$]) was visible on 46 (54.8%), but only one (2.9%) OCME case. Striations consistent with maceration scrubbing were present in two BUSM cases (2.4%), suggesting that professional preparators tried to avoid such marks (see “Trophy Remains” section, below). Bleaching was present in 15.5% of the BUSM sample, with the remaining cases most consistent with natural bone color. Dark staining that is possibly related to maceration was present on 18 cases (21.4%). This type typically is seen on the basicranium and appears to come from the interior of the bone, as it is only visible where the cortical bone is thin or through pores. It may derive from residual organic content or mold. It is also possible that bleaching chemicals are reacting with the iron content of the blood, but this hypothesis is untested. Orange staining possibly associated with maceration was present in two (5.9%) of the OCME cases and 16 (19.0%) of the BUSM cases, but the exact cause of this type of staining is also unclear (Chapter 12, Figure 12.7, this volume).

Sectioning Cuts: Remains prepared for anatomical specimens often exhibit sectioning cuts to make interior portions of bones accessible. In addition, the most common autopsy cut of the skull is circumferential sectioning for the removal of the calotte and brain (Figure 8.1). This cut typically is oriented transversely across the frontal bone just superior

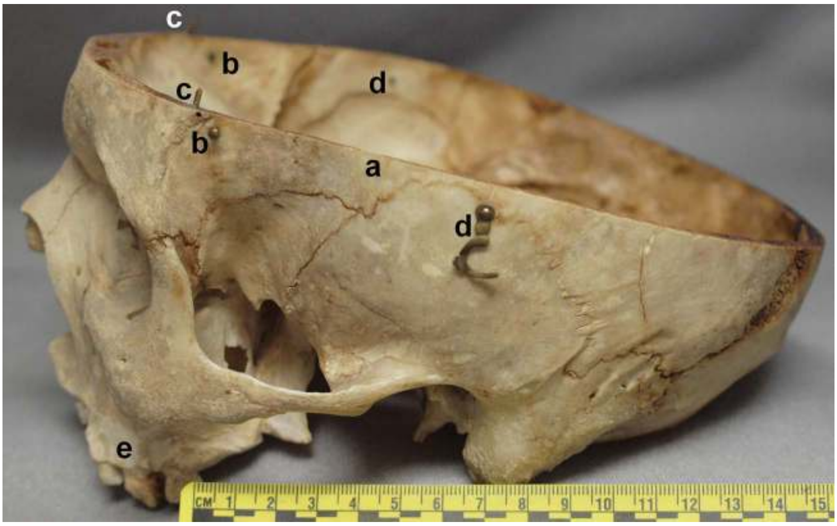

Figure 8.1 Former anatomical teaching specimen, showing: (a) sectioning cut, (b) screws for mandible springs, (c) calotte pins, (d) hooks/screws, and (e) plastic reconstruction in the alveolar area. The scale is in cm.

to the orbits and passes through the temporal bones along the squama and through the occipital planum, sometimes involving the parietals (McFarlin and Wineski 1997; Sledzik and Micozzi 1997). Vault sectioning for anatomical preparation is typically done by a flat saw blade that is large enough to span the entire vault at once, thereby producing an overall flat cut. Autopsy sectioning of the cranium leaves the brain intact, so the bone cutting must proceed circumferentially around the brain. Sectioning the vault in this manner is inherently more uneven than anatomical preparation sectioning, which does not have to avoid the brain. Autopsy sectioning also may deliberately include a triangular projection of bone along the otherwise flat margin so that the calvaria can be refit more securely afterward (McFarlin and Wineski 1997:138; Stubblefield 2011). During autopsy, the sternal ends of the ribs and the medial clavicles also may be sectioned, often by using large shears, for removal of the breast plate (Walker et al. 2002); sectioning in these locations is not typical of anatomical preparation.

The presence of these cuts also includes temporal information for determination of the postmortem interval, since mechanical devices for sectioning crania have only been employed on a large scale in modern times. The most ubiquitous of these devices is the Stryker saw, known for its deep, narrow, and vertical bone cuts, which has been available commercially only since 1948 (Breneman 1993:116). Various powered devices were patented prior to the Stryker saw and may have been employed in this role on a more limited scale. One of the earliest patents was in 1890 by Milton J. Roberts for a powered surgical saw ("Electro Osteotome", US Patent No. 436,804, Sept. 23, 1890). Prior to the commercialization of powered devices, dissections and amputations typically were conducted using either a hand saw, a hand-crank powered blade, or a gigli saw (Mr. Steve Carusillo, VP, R&D Technology, Stryker Instruments, pers. comm.).

Sectioning also may appear on postcranial remains and other locations on the skull to expose internal structures, including the mastoid processes, other sinuses, and dental development. Eleven cases (32.4%) in the OCME sample had sectioning of some kind, including a pair of femora in which both had been sectioned longitudinally; the remaining sectioned cases were all cranial. One of the sectioned crania had additional cutting to expose the left mastoid and right frontal, and two skulls without calotte sectioning had other cutting. All the BUSM crania had been sectioned, with straight and even margins typical (95.2%), and 4.8% of cases had irregular, angled, or curved margins. Additional evidence of cutting (3.6%) or drilling (4.8%) into of other cranial areas to internal features was rare.

Reconstruction Material: Plaster and other reconstructive materials are sometimes applied to any damaged, fragile, or loose areas of the skeletal elements (17.7% of the OCME sample and 25.0% of the BUSM sample). Reconstructive material has been used along the alveoli (Figure 8.1) to prevent tooth loss and the cranial sutures to prevent disarticulation. In some cases, glue also has been used to affix the sectioned calotte to the cranium.

Other: The BUSM sample, likely being newer on average than the OCME sample, showed some differences in preparation. Five BUSM maxillae (6.0%) and six mandibles (7.1%) had plastic teeth glued in to replace natural teeth, despite the skulls often being used by dental students.

Taphonomic Characteristics Related to Display and Use

Articulation-Related: Skeletal remains prepared for teaching purposes typically have drill holes and associated metal hardware from the assembly and reconstruction of the bones into anatomical order. Anatomical specimens are prepared with holes to affix all portions of a sectioned cranium, to connect the mandible, and to articulate the postcrania for mounting and display of the remains. Holes are often located on the mandible to affix it to the rest of the cranium, and the corresponding hardware holes are most frequently found on the temporal but also may be located on the frontal or sphenoid, especially when springs are used (Figures 8.1 and 8.2). These holes are generally small (approximately 2–3 mm in diameter). For display, suspension holes are most common near the anatomical landmark bregma or along the sagittal suture for hanging skeletons. Holes drilled for suspending a skeleton via a rod through the spinal column that emerges near bregma are larger (usually >5 mm in diameter) in comparison to those made for assembling the individual skeletal elements. Preparation holes tend to be circular with clean edges. Hardware on a fully articulated skeleton is usually obvious regarding its origin, although once removed, traces of its former presence may be reduced to drill holes where mounting wire passed through. Multiple types of hinged joints are used whereby the long bones can move freely in multiple planes. These often include embedding thin metal plates into slots cut into long bone ends. Wires are often used to space and secure the rib cage, with plastic materials filling in the gaps where the intercostal cartilage had been; older skeletons sometimes retained the desiccated intercostal cartilage. Felt pads are frequently glued between vertebral bodies and into the pubic symphysis for spacing. Where a postcranial element is sectioned, the two halves may be secured to each other by small hinges.

Common cranial hardware types previously have been described by Schultz (2012). (1) Plain pins sticking out of drill holes into the diploë of the calotte or inferior cranial vault (usually the latter) and usually appearing on the anterior and posterior end of the sectioned plane (Figure 8.1). Corresponding drill holes into the diploë fit the other end of the pin, which prevent the calotte from sliding along the evenly cut plane. (2) The calotte is further secured by rotating hooks attached by screws (Figure 8.1) usually into the inferior cranial vault, with small eyelets or more commonly small screws sticking out of the

Figure 8.2 Common form of mandible springs, with two holes drilled through the ramus; some also include small washers on the medial surfaces to secure the wire. The scale is in cm.

calotte. (3) Mandibular springs are usually secured to the rami by drilled holes, with the wire passing through them and bent or through a tiny washer to secure it (Figure 8.2). The corresponding screws in the cranial vault (see above) usually allow the spring to be looped around them, so that the mandible can be removed or extended without removal. Mandibles have also been articulated by drilling holes into the condyles and mandibular fossa to hold either end of a wire that could bend and allow some mandibular extension.

Some type of hardware, most of which was consistent with brass and some with steel, was present in 18 cases (52.9%) of the OCME sample. Only one case with hardware was not accompanied by drilling into bone, but this case used improvised wire to attach a mandible to a cranium. Other drilling (i.e., including empty holes) was present in 19 cases (55.9%). Suspension holes were present in five cases (20.8% of crania that had intact superior vaults). Calotte pins were present in 70.2% of the BUSM sample, and calotte hooks paired with eyelets, posts, or screws were present in 71.4%. Mandible springs were present in 69.0% of BUSM cases, and 4.8% were strung with miscellaneous wire, possibly remnants of mandible springs or replacements for lost springs. Other less prevalent configurations are indicated in Table 8.2. Suspension holes were present in only two BUSM cases (2.4%), likely because these holes are for skulls associated with an entire suspended skeleton; the two skulls therefore were likely separated from a previously complete, suspended skeleton. Four OCME cases (11.8%) had iron (red) or copper (green) oxide staining, associated in each case with articulation hardware made of steel or brass, respectively.

Anatomical Markings, Writing, and Labeling: Anatomical markings on skeletal remains are a common addition to the preparation of modern commercial anatomical specimens. These markings primarily consist of labeling anatomical features such as muscle attachment points, arteries, veins, and nerves. Writing often includes names or serial numbers from the company distributing and selling the remains. Older specimens sometimes have the location of preparation or individual who prepared the remains. Paint specks or marks resembling paint are also commonly present on anatomical remains from curation, molding materials, and accidental exposure. Unintentional marks or incidental writing also can be found on anatomical and teaching specimens, especially around locations involving craniometric landmarks and measurements, the instructions for which in many cases advocate the use of a temporary pencil mark to indicate a midpoint (Buikstra and Ubelaker 1994), which may be left behind.

Labeling of either specimen numbers or supplier company information was present in six cases (17.7%) in the OCME sample, including one postcranial case (two sectioned femurs) stamped in black ink with "Clay-Adams, Inc.; New York, N.Y.", a long-time supplier of anatomical and other research equipment now owned by another corporation (Becton, Dickinson and Company 2021). Another case had a serial number and "Cleveland University" hand-labeled in blue ink. An attached label indicating the anatomical supply company was present on one case in the BUSM sample. Stamped information or labels were present in 10.7% of the BUSM sample, and labeling of anatomical structures was present in 16.7%. One or more specimen numbers were written on 78.6% of the BUSM skulls. Since commingling of different crania-calottes-mandibles occurred, some specimens had non-matching numbers.

Coating: Four OCME cases (11.8%) had some type of exterior coating or varnish, three of which may have been part of original preparation. The fourth was crudely applied and was likely a modification occurring long after original preparation.

Taphonomic Characteristics Related to Curation

Handling Alteration: Remains prepared for anatomical or display purposes frequently exhibited postmortem alteration from repeated handling, especially in the form of breakage along the fragile portions of the skull (the eye orbits, interior nasal area, styloid processes, alveolar bone, and zygomatic processes). Damage also may be present around the areas of articulation as a result of abrupt or repeated contact between the moveable parts. As indicated above, broken teeth are common, as the springs joining the mandible to the cranium often cause the mandibular teeth to close forcibly against the maxillary teeth when care is not taken. Fully articulated skeletons are difficult to handle and transport, and damage can occur when limbs are not stabilized and are free to swing. Such remains, by their very nature, exist to be manipulated by multiple persons often initially unfamiliar with their fragility. The same bones often are used in academic settings for decades, slowly acquiring destructive modification over that span.

The cases were rated on the overall preservation of the bone. Twenty-eight OCME cases (82.4%) had skeletal elements that had retained their organic sheen, five cases (14.7%) had chalky surface texture, and one case (2.9%), a complete mounted skeleton, had some areas of organic sheen with localized areas of chalky/friable bone. Among the BUSM sample, retained organic sheen was most typical (95.2%), followed by chalky appearance (3.6%), and mixed condition (1.2%).

Ink and pencil marks also were found on 16 (47.1%) of the OCME cases. While some could have been incidental, some appeared at the locations of commonly learned anatomical structures, including foramina. This included labeling a structure in pencil. No labeling of anatomical structures by the original preparators, however, was found among this sample. Stray ink and pencil marks also were abundant in the BUSM sample: ink marks were

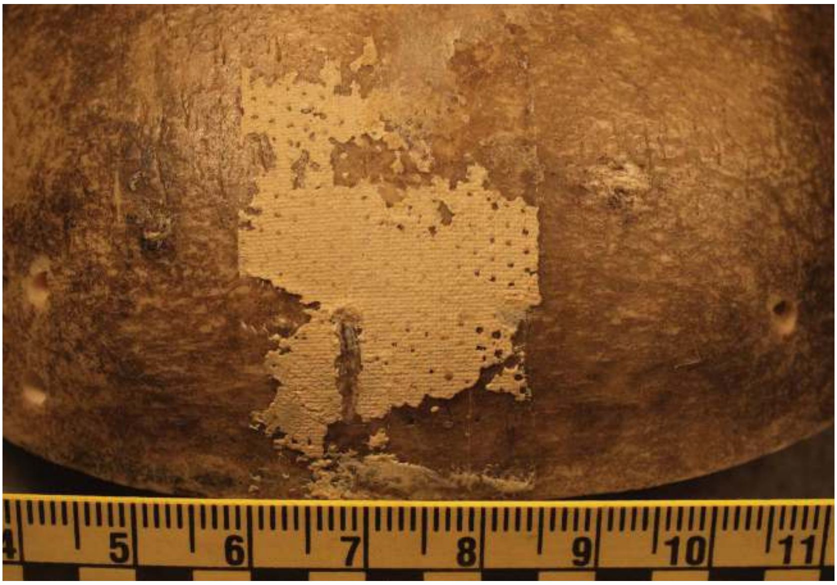

Figure 8.3 Sectioned calotte of a former anatomical teaching specimen, showing dark surface staining and tape residue. The scale is in cm.

present in 76 cases (90.5%), and pencil marks were present in 69 cases (82.1%). Legible ink writing that was not from the original skeletal preparation was present in 32 cases (38.1%), and pencil writing was present in 24 cases (28.6%). Writing could be associated with anatomical structures, later specimen labeling, or unrelated/unknown purposes. Small areas of paint (that could not have derived from repurposing; see below) were present in three BUSM cases (3.6%).

Adhesives, Tape, and Related: Glue and other adhesives, such as rubber cement or residue from adhesive tape, are used frequently in anatomically prepared human remains to reconstruct broken or loose elements throughout normal use. Remnants of adhesives (Figure 8.3) also can be found on anatomically prepared specimens after features have been labeled for exemplars during instruction and from test preparation (or to cover serial numbers known to the test-takers). Dust, debris, and dirt adhere more readily to these residual adhesive areas, giving them a darkened appearance. In other cases, the tape or adhesive prevents the formation of patina (see below) and creates a lightened area of bone underneath. Frequently, the precise outline of the adhesive material is preserved, and areas tend to be symmetrical, rectangular in shape, and have distinctly outlined corners or edges. Tape residue was present in two cases (5.9%) of the OCME sample. Taping or tape residue was present in 21.4% of the BUSM sample and was usually placed to keep a sectioned calotte attached or to secure a broken area. Gluing was present in 11 OCME cases (32.4%). Glue was applied to repair postmortem damage, secure anterior teeth (possibly from original anatomical preparation), or, in one case, to secure the mandibular condyles to the mandibular fossae. Gluing of the teeth (77.4%) was most common among the BUSM sample, either to hold them in place or repair them after breakage, and it is also possible that some socket gluing was part of original preparation. Other cranial regions had gluing in 27.4% of the BUSM cases.

The BUSM sample included traces of translucent dental wax (7.1%) and mounting clay (4.8%). These substances were more likely introduced by forensic anthropology graduate students, who also sometimes use this collection but to a lesser degree than medical and dental students. Dental wax can be used for temporary repairs and to secure loose teeth and calvaria for analysis and photography, and clay columns are often used as a pedestal for a cranium being recorded by a three-dimensional digitizer.

Dust: A thick coating of dust is referred to as *attic dust* because of long-term accumulation from storage. Frequently, it is found on internal structures due to exposure from the cuts made during preparation. The pattern of dust accumulation found on the remains can indicate how the skull was displayed or stored and how regularly it was handled. Endocranial dust accumulation suggests that the skull was stored without the calotte in place and protecting the internal structures. Ectocranial dust accumulation is often found along the top of the skull, along the inferior portion of the eye orbits, at the base of the zygomatic arches on the temporal bones, and inside the nasal aperture. Specimens handled less frequently during prolonged periods of curation can be expected to have more dust buildup present. Seven OCME cases (20.6%) and 16 cases (19.0%) of the BUSM sample had significant dust present. A further four OCME cases had other kinds of sediment adhering.

Patina: This taphonomic effect is an accrued darkened film as a result of long-term exposure to dust and handling, the composition of which includes oils and other substances from human skin (Chapter 12, Figure 12.5f, this volume). This may be accompanied by a glossy *polish* or burnish, as a result of repeated handling. The presence or degree of the patina or gloss largely depends on how often the remains were handled. Skulls displayed as art or curiosities generally are not handled as often as teaching specimens. Differential staining also may result from the processing method or from the remnants of the aforementioned adhesives. Care should be taken not to confuse the darkened appearance from differential staining or patina with soil staining from burials. Twenty cases (58.8%) of the OCME and 62 (73.8%) of the BUSM samples exhibited significant patina buildup. In some cases, the patina buildup in places subsequently gets worn off the more projecting portions of surfaces (*reverse patina*), which manifests as paler areas within otherwise patinated areas. Overall color change of the bone, besides superficial patina, was medium brown in eight OCME cases (23.5%) and dark brown/gray in five cases (14.7%; Figure 8.3), with the remaining 21 cases (61.8%) of natural bone or bleached color.

Shelf Wear: This taphonomic effect is caused by unintentional, accrued postmortem processes affecting the base of the cranium, including the occipital condyles, mastoid processes, and inferior mandibular margin, specifically characterized by erosion and flaking of the outer cortical bone from repeatedly setting the skull down on hard surfaces (Figure 8.4). Repeated rubbing and wear on a surface also can create a dense, smooth, shiny, whitened appearance similar to ivory. Postmortem damage to teeth, however, is very common and usually cannot be ascribed directly to this process. Shelf wear was present in eight OCME cases (33.3% among cranial elements that included their inferior portions), including two cases that only included the mandible. Among the BUSM sample, shelf wear was found most often on the occipital condyles (51.2%), followed by the gonial angles (29.8%), mastoid processes (21.4%), or other location (13.1%).

Other Breakage: A more detailed survey of postmortem breakage could be made for the BUSM sample (Table 8.2). The difficulty and expense of maintaining a collection of anatomical specimens may cause skulls to be utilized for many years, until the specimen is retired from active use. While sturdy, heavily padded storage boxes are provided, skulls are regularly signed out and transported home for study. The years of handling and

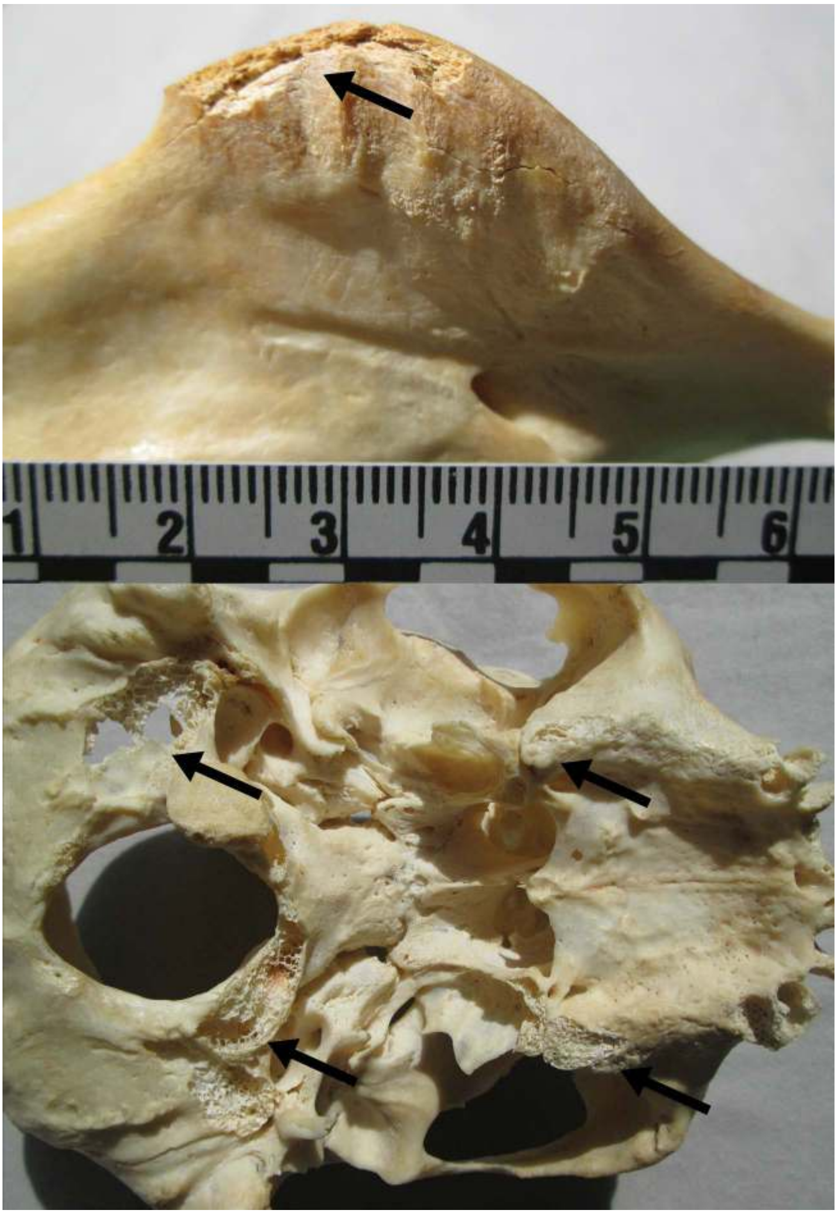

Figure 8.4 Examples of shelf wear (arrows). The inferior mandible (top) and cranium (bottom) show damage typical to surfaces from repeated handling, in this case from years of teaching in a medical school.

transportation cause heavy attrition among the weaker areas of bone. Every skull specimen with dentition showed damaged teeth, and evidence of some degree of postmortem tooth loss in 95.2% of cases. The next most damaged areas were the styloid processes (96.4%), followed by the lacrimals and thinner orbital structures (91.7%), vomer (88.1%), endocranial structures (84.5%), nasals (83.3%), maxillary (76.2%) or mandibular (69.0%) alveolar margins, inferior nasal conchae (64.3%), mandibular condyles (61.9%), and cranial vault (31.0%), with other areas in lesser amounts.

Other Taphonomic Effects: In two BUSM samples, portions of disposable plastic cinches (i.e., "zip ties") were affixed around zygomatic arches, although these might not be retained long term in specimens in private hands. Pipe cleaner fragments were present in two (2.4%) of the specimens; these are used to trace the paths of foramina when learning anatomical structures. Due to a non-recurring accident of storage that happened just before analysis, four (4.8%) BUSM skulls (and their storage boxes) had mold growth, which was removed during analysis. Three (3.6%) BUSM skulls had light brown surface stains most consistent with spilled coffee.

Taphonomic Characteristics Related to Later Repurposing of Remains

Since the BUSM cases had no chance to be repurposed, only the OCME sample shows any changes from later use in a different context, which is common among remains of this type and will present as a palimpsest of taphonomic effects that may be ordered temporally (Chapter 20). Remains were frequently used as display items in the form of a candle holder or at least as part of a display with candles nearby; seven cases (20.6%) had candle wax adhering (Figure 8.5), and four cases (11.8%) had thermal alteration (Figure 8.6). In particular, one isolated sectioned calotte had thermal alteration (three calcined areas surrounded by areas of carbonization) on the endocranial surface and adhering fine, gray sediments most consistent with ash; the overall pattern fits best with its having been used as an ashtray. Six cases (17.7%) had some kind of paint crudely applied, including minor amounts of red pigment with gold metallic flakes in one case and spatters of thin brown liquid (possibly wood stain) on another. Other cases had larger areas covered with pigment, including a cranium completely smeared with black pigment (possibly shoe polish), or another case of a cranium and two postcranial bones with gold spray paint all over and varnish on some areas of the cranium. One partial articulated skeleton case had gray paint applied all over and

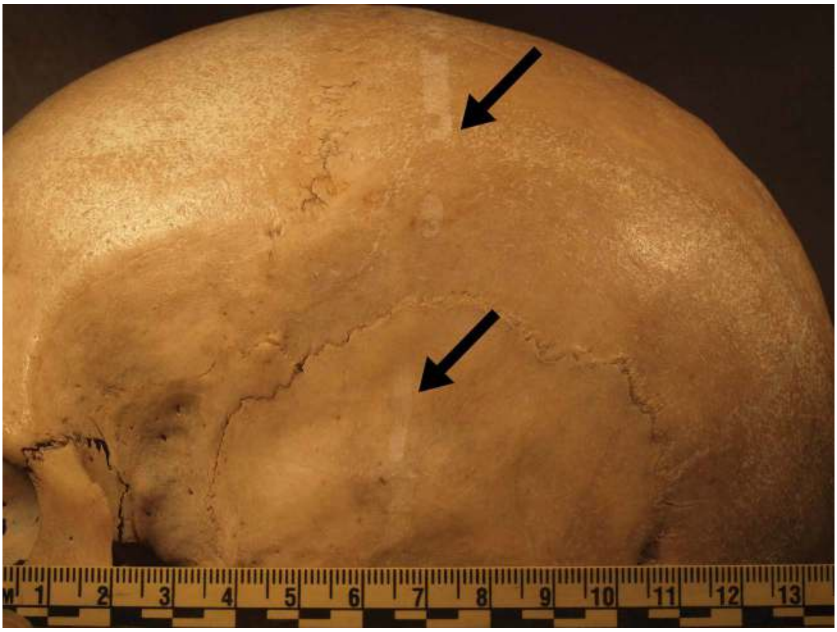

Figure 8.5 Candle wax (arrows) from later repurposing as a display object on the vault of a former anatomical teaching specimen. The scale is in cm.

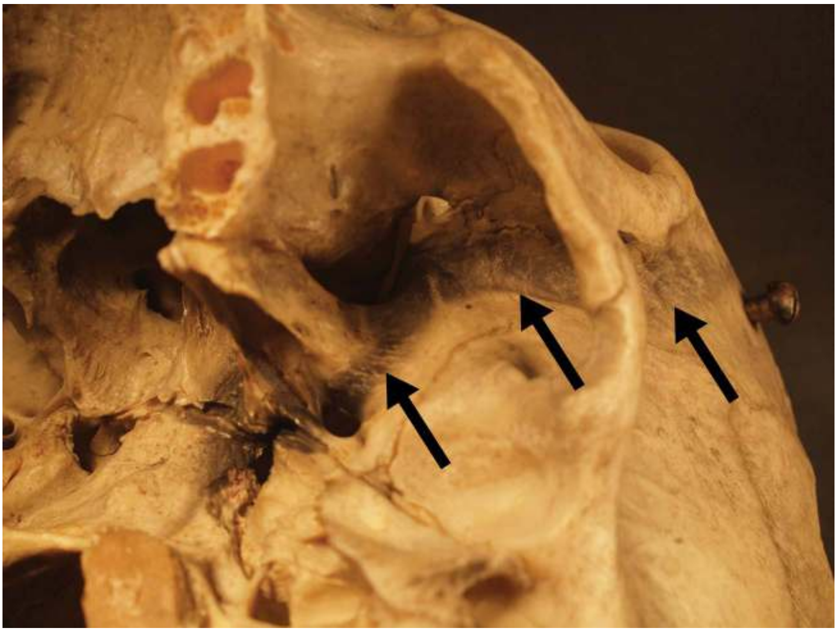

Figure 8.6 Thermal alteration in the form of candle soot (arrows) from later repurposing as a display object, on the basicranium and left vault of a former anatomical teaching specimen.

the cranium wired for use as a lamp, including a small light socket and plastic compound filling in the posterior eye orbits. One skull had multiple chopping marks meant to make its provenience more interesting (in this case, reportedly the Battle of Agincourt). There are no clear limitations on how human remains can be repurposed, so forensic examiners may encounter all manner of artistic expression or unanticipated use of human skeletal remains.

Contemporary Ritual Remains

In the USA, multiple instances of human remains encountered from ritual contexts have been attributed to the practice of Santería/Ocha and Palo Mayombe, with the former being perhaps the largest sect of the extensive underground religions (Brandon 1993). Though both derived from Afro-Cuban traditions and share some similarities, the two religions are distinct in practice and use of human remains, which translates to different material culture signatures (Winburn et al. 2017). These cases are most frequent in cities with large Afro-Caribbean populations, especially New York, Miami, Los Angeles, Chicago, Boston, and Washington, DC, among others (Brandon 1993; Wetli and Martinez 1981, 1983). While human osseous remains from other less numerous or less formal modern ritual practices may no doubt be encountered in forensic settings, these two ritual systems often generate specific taphonomic characteristics that may indicate the origin of some collections of skeletal remains.

History of Santería/Ocha

The beliefs of Santería/Ocha stem from the African slave trade in colonial Cuba and the combination of Christianity, influenced largely by Spanish Catholicism, with the African

Yoruba religion, primarily of Nigeria, into what is referred to as a syncretic faith. The early, or formative period of Santería in Cuba developed from about 1760 through 1870, after which time Cuban slavery slowly became abolished, and a period of transformation brought the religion into the predominant form (Brandon 1993). Following the Cuban Revolution and resultant diaspora, Santería began to take root in New York in 1959 (Brandon 1993).

Santería also has been referred to as *Regla de Ocha* ("Rule of Ocha"; variably spelled *Ochaö*) and *Lucumí* ("friendship"; variably spelled *Lukumi*), an ethnic term that was used in Cuba to describe the Yoruba slaves and their culture (Brandon 1993; De La Torre 2004). Hybrids of the syncretic religion developed as the Yoruba slaves were transferred to different Caribbean regions, such as Voodoo (variably *Vodou* or *Voudun*) in Haiti and New Orleans as expressed through French Catholicism (De La Torre 2004).

According to the principles of Santería, the deities are secondary gods known as the *orishas*, of which there is no exact number, but the pantheon may include around 20–25 in Latin America and range from 400 to more than 1000 in Africa (De La Torre 2004; González-Wippler 1989). To mask the practice from the slave owners, the *orishas* were associated with Catholic saints and celebrated on the respective Saint's Days, hence the term "Santería", literally meaning "the way of the saints". The association of the *orishas* with saints continues to be practiced, even though Santería is becoming less of an underground religion.

Specific *orishas* are associated with certain colors and sacred objects and offerings, to include preferred animal sacrifices. Initiates of Santería receive beaded necklaces (*collares* or *elekes*) in the respective color sequences for five major *orishas*, followed by those of additional *orishas* if their protection is deemed necessary (González-Wippler 1989). The finding of such necklaces in association with ritual remains or altars has been reported in investigations by Gill et al. (2009) and Wetli and Martinez (1981).

Several *orishas* are invoked during a single ritual by the *santeros*, or priests. One of the most influential *orishas* is *Elegguá*, for the Yoruba word meaning "messenger of the gods." *Elegguá* is the patron saint of pathways and crossroads, and he is believed to be the intermediary between humans and *Olodumare*, the one God of Santería. As such, *Elegguá* is always the first *orisha* invoked during a ritual so that he will pass on the requests of the practitioners, and a portion of every sacrifice is offered to him. He is referred to as the trickster, in part because of the stories that he would often hide behind doors of houses to eavesdrop for information. The colors of *Elegguá* are red and black, and his necklace consists of three red beads alternating with three black beads. His associated objects, offerings, and animal sacrifices are not limited to roosters, goats, deer, opossum, coconuts, rum, toasted corn, cigars, whistles, guns, and children's toys. This *orisha* is represented as a clay or cement head with a face made out of cowrie shells, and the object may often be found behind a door, a finding that is further verified in a case by Wetli and Martinez (1981).

When a *santero* dies, a group of *santeros* gather and consult the *orishas* through cowrie shells to determine how to discard the previous owner's paraphernalia, with options of burying the objects with the person, giving them to an heir, or giving them back to nature by tossing them into a river or ocean. This action may account for cases involving bags of bones with other items found along riverbanks, such as reported by Gill et al. (2009).

While human remains can be associated with *orisha* assemblages, it is not as common practice as in Palo Mayombe and is typically restricted to the smaller skeletal elements (e.g., phalanges) (Winburn et al. 2017). Ritualistic *orisha* thrones consist of assemblages and *soperas* (tureens) to honor the *orishas* (Winburn et al. 2016).

Palo Mayombe

Another popular spiritual hybrid developed from the slave trade as African beliefs originating from the Kongo culture of central Africa were syncretized with Christianity to form Palo. The practice of Palo uses magic associated with *brujería*, or witchcraft, and it is said to be "the dark side of Santería" by non-practitioners (De La Torre 2004:27), although they are separate belief systems. In addition, practitioners of Palo can progress later as initiates of Santería, while the reverse is not allowed (De La Torre 2004; Murrell 2009). Leaders of Palo often may choose to incorporate myths and symbols of Santería into their own practice, depending on individual interpretations (Murrell 2009).

Palo is a Spanish term for "branch" or "wooden stick" and derives its name from the incorporation of wood branches and herbs in its spells. The branches or sticks are part of the foundation used to fill the ceremonial cauldrons, pots, or sacks, known as *prendas* or by the African name *ngangas* (Figure 8.7). Artifacts included in the *prendas/ngangas* include *bilongos* (magical works), soil, stones, insects, azogue (metallic mercury), animal carcasses, or blood (De La Torre 2004; Winburn et al. 2017). The most important aspect, and the key differentiating factor from Santería, is the inclusion of the "*nfumbe*—the dead one, or the force of the dead—represented by human remains" (Ochoa 2010; Winburn et al. 2017:5). A variety of other items will be added for the spells such as coins, candles, scraps of a person's clothes, cigar butts, and foodstuffs like rum, lime, and wine besides the many herbs and spices. Further, quicksilver (mercury) is often added to give the spirit speed, and the remains of a dog will help the spirit in its search (González-Wippler 1989). An *ebbo* is food, herbal, and animal offering requested by the *orishas* through divination, which includes sacrificing animals and their blood (Pokines 2015b).

Palo Mayombe is one of the major sects of Palo. The influence of Christianity on Palo Mayombe is reflected through the division of the good "baptized" versus the bad "unbaptized" branches of the practice. The "baptized" add holy water to their *ngangas* and only

Figure 8.7 The practice of Palo Mayombe uses ceremonial cauldrons such as these, containing the remains of RMEO-1 and sacrificial objects. (Image courtesy of G. Hart, State of New Jersey Regional Medical Examiner's Office, NJ.)

work with good spirits of the dead. This Mayombero Christiano sect of Palo Mayombe uses “white magic”, and it can be distinguished from evil magic, because the altar will always have a crucifix associated with it (Wetli and Martinez 1983). The “unbaptized” work with evil spirits, as in those from criminals or the insane, who would be more likely to fulfill their malevolent requests (De La Torre 2004; González-Wippler 1989). The spirits are obtained through a bone of the deceased, and in return for the favors, blood and animal sacrifices are offered. Notably, a railroad spike is a symbolic item of the “unbaptized” *paleros* (i.e., Palo practitioners).

Of the several steps required in the initiation ritual to become a *palero*, the final ordination may be of forensic interest. Bones typically included are the complete skull, crania only, and long bones, with the skull representing intelligence and the limb bones representing mobility (Winburn et al. 2017). A human tibia wrapped in black cloth is received as a scepter used to invoke the spirits of the *nganga*. In choosing spirits of the dead for the *nganga*, human remains from a cemetery are usually acquired from recent corpses whose identity is known to the *palero*, in hopes that the brain is present and to be sure that their requests will be followed. Fingers, toes, and ribs are often taken along with the head and tibia. There is no set preference as to the biological or social affiliation of the deceased individual, but it is said that remains from a White person are favored in beliefs that their brains are “easier to influence than that of a [B]lack man and that it will follow instructions better” (González-Wippler 1989:244). Winburn et al. (2016), however, found that ancestry was mostly non-White in their case sample. Geographic area may play some role in the ancestry of human remains used, if they are acquired locally from cemeteries. When a *palero* dies, his *nganga* is either passed on to another or dismantled and buried in the woods, preferably near the base of an anthill, and the earth is topped with rum and chicken’s blood (González-Wippler 1989). This is done to constrain the associated evil spirits (González-Wippler 1973:30; Wetli and Martinez 1983:633).

These Afro-Caribbean religions lack a central organization or formal dogma; therefore, the beliefs and practices will vary in different regions and even among neighboring house-temples. Variations in these religions also developed from the combination of assorted African tribes that were united because of the slave trade in the Caribbean. When human remains are involved in the rituals, the practice is more likely related to Palo. The beliefs of Palo focus largely on veneration of the dead, namely, by invoking their spirits (known as *nkitas* among other synonymous terms). Worship, however, does include some counterparts of the *orishas*.

Comparative Analysis of Ritual Remains

Generalizations from the religious beliefs of Santería and Palo Mayombe support the interpretation of taphonomic features observed on case studies of ritual remains from nine reported investigations with a total of 15 skulls/crania, along with other human and nonhuman remains. Wetli and Martinez (1981) described five ritualistic cases involving a total of seven skulls and other human and faunal remains from the Dade County Medical Examiner’s Office in Miami, FL, designated here as DCME-1–5. Gill et al. (2009) described two cases consisting of three skulls from the New York City Office of Chief Medical Examiner (OCME) and Department of Forensic Medicine, designated here as OCME-1a, 1b, and 2. Ms. Gina Hart contributed anthropology reports from the State of New Jersey Regional Medical Examiner’s Office (RMEO) in Newark describing two cases with a total of five human skulls, designated here as RMEO-1a, 1b, 1c, 2a, and 2b, along with many other human and nonhuman faunal remains. Pokines (2015b) reported an isolated case of Palo Mayombe from Massachusetts submitted to the Office of the Chief Medical Examiner, Boston, designated here as OCME-B. These cases were compared to a recent analysis of the largest compilation of ritual remains, coming from the University of Florida's CA Pound Human Identification Laboratory (CAPHIL) in Gainesville, that detailed 42 retrospective cases from 1986–2014 (Winburn et al. 2016, 2017).

Commingling

It is apparent that ritual cases will involve the remains of multiple individuals dispersed over several cauldrons or vessels, although in Palo Mayombe the *prenda* cannot share *nfumbe* (the human remains) (Winburn et al. 2017). Ceremonial cauldrons were encountered in 30.2% (n = 13) of the CAPHIL cases (Winburn et al. 2016) and in OCME-B (Pokines 2015b). In RMEO-1, all three skulls were without their calvaria, and three nonmatching calvaria were present. In addition, postcranial remains found in a white sack at the residence were matched to RMEO-1c, and postcranial elements from another individual were reassociated from throughout the cauldrons and vessels (*prendas/ngangas*) of the case (Figure 8.7). Of interest, both individuals were able to be identified by pair-matching, articulation, and taphonomic similarities (e.g., coloration) of elements compared to remains recovered from disturbed cemetery crypts with deaths dating to 1930 and 1935. Winburn et al. (2016) reported commingling (MNI >2) in 8 of 42 of the CAPHIL cases (19%).

Human remains also tend to be commingled with nonhuman remains, as animal offerings and sacrifices are a fundamental aspect of Santería and Palo Mayombe rituals. Nonhuman remains associated with the cases include reports of chicken heads and bodies, a duck head, and several other avian species, a turtle carapace/plastron, snake, goat skulls, dog heads, deer antlers, and cow horns, along with several unidentified nonhuman bones. Winburn et al. (2016) also encountered other primate bones, larger mammals (cow, sheep, goat, ungulates), rodents, bats, and reptiles in the CAPHIL cases (44.2%).

Biological Profiles

As stated above, human remains used for ritual purposes are not limited to a specific biological profile. Two Black males (DCME-1 and -2a) and one White female (DCME-4) were reported by Wetli and Martinez (1981), and Gill et al. (2009) reported probable male and probable female remains of indeterminate ancestry among OCME-1. The skulls involved in the RMEO cases were determined to be of three White males (RMEO-1a, -1c, and -2b) and two females and one White (RMEO-2a) and one either White or Hispanic (RMEO-1b). All the crania were determined to be from adults or older adults, although a subadult calvaria also was present among RMEO-1.

In comparison, Winburn et al. (2016) reported primarily adult males of non-European ancestry, but CAPHIL cases included females and juveniles as well, and estimations of ancestry were more difficult in circumstances not including the crania. Their sample was 88.7% adults, and the remainder were juveniles (Winburn et al. 2016). Most of the sample were classified as male (62.0%), although 8.0% were considered indeterminate. Ancestry varied, with 34.0% of the sample being of African descent, 35.9% Asian/Native American, 17.0% European, 17.0% Hispanic, and 28.4% being classified as non-US population, non-European, other, or unknown (Winburn et al. 2016).

Antemortem tooth loss was reported in cases of older adults. RMEO-1a, -1c, and -2a are edentulous crania, and two maxillary dentures were included in RMEO-1. Antemortem lesions noted on RMEO-1b suggested a disease such as tuberculosis. There were no reports of perimortem trauma observed among the cases.

Taphonomic Characteristics of Ritual Remains

Remains acquired for ritual practice may derive from several contexts and therefore will exhibit some taphonomic effects related to their acquisition. The majority of human remains used for ritual purposes are derived from cemetery contexts (i.e., grave robbing) or to a lesser extent from anatomical suppliers (Winburn et al. 2017). The anatomical specimens will exhibit some of the taphonomic effects described above, including anatomical preparation, hardware, patina, adhesive, and writing/labeling.

Botánicas supply human remains for Afro-Cuban, Caribbean, and Latin American religious practices. For example, the practitioner using DCME-1 had supplied a receipt of purchase for the item from a *botánica*. One cranium from DCME-3 had a broken spring and screw attached to the mandible with a corresponding screw in the maxilla (Wetli and Martinez 1981), and five CAPHIL cases (11.6%) included anatomical hardware and/or holes (Winburn et al. 2016), suggesting their origin as anatomical specimens. The observed taphonomic features on the other remains have been categorized as relating to either previous interment or cultural practices.

Taphonomic Characteristics Related to Previous Interment

Gill et al. (2009) reported that the remains from OCME-1 and -2 are consistent with having a historical origin from a long-term burial, which is a similar finding for the RMEO cases. Taphonomic effects consistent with a previous burial often lack features of environmental exposure, such as scavenging, with the major exceptions of adherent soil and soil staining (Chapter 5). Winburn et al. (2016) also noted soil staining, sun bleaching, warping, root damage (etching or staining), artifact staining, and coffin wear. Over a third (36.2%) of the CAPHIL sample is attributed to modern cemetery origins or historic and archaeological contexts (10.6%).

Adherent Soil: Dried soil and dark staining were reported in most of the sample here as well as in Winburn et al. (2016), with 62.8% (n = 27) cases exhibiting soil staining and 48.8% (n = 21) of cases having adherent soil. Soil was abundant around the orbits, nasal aperture, and other openings. In some cases, adherent soil also may be attributed to cultural modification, as soil is an integral part of the cauldron foundation, or it may occur postdepositionally with discarded remains. It is most likely that a thick coating of soil and dark staining on the remains are related to previous interment.

Autopsied or Embalmed: The preservation of autopsied and embalmed remains is highly variable and thus, not a reliable indicator of postmortem interval (Chapter 5). Embalming hinders and alters the typical decomposition process (Mann et al. 1990), often leaving remnant desiccated tissue. Berryman et al. (1991) noted that evidence of embalming includes adhering head and facial hair; fungal growth particularly on the hands and face from cosmetic make-up and elsewhere from the dark, moist environment; flaking of the skin from continual shrinkage; flaking and erosion of cortical bone from changes between wet/dry episodes and "pressure point" contact with the coffin surface (i.e., coffin wear; Chapter 5); differential decomposition; and brain preservation.

Many of these traits were described in these cases. The presence of desiccated tissue was noted on RMEO-1a and 1c, and on several postcranial elements associated with the case, especially articulating finger bones and vertebrae. Desiccated soft tissue was found in 4.7% (n = 2) of the Winburn et al. (2016) cases. Further, clumps of hair were adhering to RMEO-2b (Figure 8.8). Cortical exfoliation or flaking were reported on three cases (OCME-1 and -2 and RMEO-2), possibly due to coffin wear. Hair and possibly fur, were also encountered by Winburn et al. (2016) in 14.0% (n = 6) cases. In addition, a mummified brain present in the cranial cavity was reported in one case (DCME-4). Fungal growth was not reported; however, a dark greenish coloration was observed on remains from RMEO-1, which may be related to embalming. As noted earlier, the three crania from RMEO-1 are without their calvaria, but three other calvaria are present, and all but one of these (RMEO-1b) are consistent with the smooth-cut sectioning done by a Stryker saw during autopsy. Three cases (7.0%) had evidence of autopsy cuts in the CAPHIL sample (Winburn et al. 2016).

Figure 8.8 Soil and clumps of hair adhering to the RMEO-2b cranium. (Image courtesy of G. Hart, State of New Jersey Regional Medical Examiner's Office, NJ.)

Taphonomic Characteristics Related to Cultural Practices

Associated and Residual Artifacts: Indications of ritual remains are obvious when found in the context of altars or *prendas*. Prolonged contact with other ceremonial offerings may leave residual traces on the remains that may still be present when they are taken out of that context or discarded.

After taking a radiograph of OCME-2, Gill et al. (2009) discovered a glass jar containing mercury within the mud-filled cranial vault. Winburn et al. (2016) encountered mercury in 16.3% (n = 7) of their sample. The cranial cavity of RMEO-2a was full of plastic, paper, and miscellaneous objects visible through the foramen magnum.

Natural vegetation, likely associated with herbs being added to the altars and *prendas*, were noted in several cases. Wetli and Martinez (1981) noted the presence of dried grass on three crania (DCME-3a, -3b, and -5). Green leaves, likely of an herbal nature, were present within the cauldrons and crania of RMEO-1, while particles of dried grass were apparent on the RMEO-2b cranium. In these cases, postdepositional adherence of dried grass seems less probable, as the DCME remains were encountered within bags or wrapped in cloth. The presence of these botanical remains due to previous interment, however, cannot be excluded.

Direct contact with copper and corroded metal items can result in a green oxide stain (DCME-3) or rust-colored stain (DCME-2 and OCME-1b), respectively (Chapter 12). Winburn et al. (2016) encountered two cases with metallic staining: one with iron and one with copper. Feathers were abundant over most of the items from RMEO-1, were reported for DCME-2, and were in 51.2% (n = 22) of the Winburn et al. (2016) cases. Glitter was also noted throughout RMEO-1 and 4.7% (n = 2) of the Winburn et al. (2016) cases.

Blood residue can be expected, as it is a sacred offering of Santería and Palo Mayombe, and it may transfer from association with recently sacrificed animal remains. Blood was noted in DCME-1, DCME-4, and 30.2% (n = 13) of the Winburn et al. (2016) cases. The presence of blood may be underreported, or less obvious, when dried on remains with thick adhering soil or when combined with other taphonomic staining sources.

Evidence of burning and use of candles (e.g., wax) can be expected with ritual use of remains. In the CAPHIL cases, 14.0% (n = 6) displayed burning, and 11.6% (n = 5) had wax adhering to one or more bones. Wax is associated with both Ocha and Palo rituals. Winburn et al. (2016) also documented high frequencies (>10% of sample) of colored beads, sticks and wood, smooth stones, coins, knives/machetes, shells/cowry shells, seeds/beans, and unspecified metal objects. Less common material culture items (<10%) encountered in the CAPHIL cases include horseshoes, railroad spikes, faunal horns, statues, models of human skulls, figurines, wood carvings, metal, chains, paper charms, crosses, cotton fabric, plaster, handcuffs, ceramic vessels, ribbons, eggs/eggshells, candles, crowns, cigars, gourds, glass, and nautical paraphernalia including fishhooks, nets, and miniature ship models, life preservers, and mermaids (Winburn et al. 2016). Pokines (2015b) encountered additional items including a lock, key, jewelry (ring), and a glass fragment.

Odor: A foul odor was noted on the remains of RMEO-1 due to contact with a mixture of items within the cauldrons including herbs and spices, rotting fruit, decomposing animal carcasses, and likely from incense and candles.

Graffiti: Certain symbols and emblems are associated with the spells of Palo Mayombe. One popular emblem is of the Earth and four cardinal points to signify the crossing of ways, where the evil spell is sent to the victim (González-Wippler 1989:242). The symbols include circles, arrows, and crosses, which may be made from chalk, paint, blood, or other

Figure 8.9 Saw marks atypical of autopsy cuts are present in the cranium of RMEO-1b. Included with the case was a dog (*Canis familiaris*) skull. (Image courtesy of G. Hart, State of New Jersey Regional Medical Examiner's Office, NJ.)

media. These symbols are present on the cranial vaults of OCME-1 and within a cauldron of RMEO-1, while other similar symbols are present on the blades of machetes associated with both cases. Graffiti was also noted in the CAPHIL cases, with one displaying labeled anatomical landmarks, one with indiscriminant ink, and one with black markings consistent with *firmas* (spiritual paths on which the spirits travel) (Winburn et al. 2016). Paint was found on an additional three cases and included black, gold, orange, blue, and red pigments (Winburn et al. 2016). Painting included references to *prendas* (e.g., "7Rayos" referring to Siete Rayos and symbols of the *dikenga* (ritual markings associated with spiritual repose) (Winburn et al. 2016). Pokines (2015b) also documented labeling including the terms "malo," "vaca," "jaguey," "llamao," and "moruro" found on sticks associated with human remains in a cauldron.

Postmortem Cutmarks: Postmortem cutmarks or saw marks to the ends of long bones are common among ritual cases and includes several elements of RMEO-1 and -2 and DCME-2 and -4. Likewise, rough and inexpert saw marks are attributed to the sectioning of the calvaria of both DCME-5 and RMEO-1b (Figure 8.9). Winburn et al. (2016) documented 34.9% (n = 15) cases with postmortem sharp force trauma such as knife and saw damage indicative of disarticulation and non-autopsy removal of the calotte.

Summary: Taphonomic Characteristics of Ritual Remains

These findings indicate that the taphonomic characteristics relate to the original source of the remains and to their later alterations through ritual use. Ritual remains associated with Santería or Palo Mayombe tend to originate from burials or are acquired as anatomical specimens. The recognition of burial remains may include thickly adherent soil and desiccated tissue and hair remnants from the embalming process. The most common artifacts resulting from ritual use include adherent grass and herbs, blood residue, feathers, and drawn symbols. In addition, artifacts may be lodged within cranial vaults. Remains also may acquire a foul odor from the assorted collection of items within the cauldrons, especially from decomposing animal carcasses and rotting fruit. The identification of ritual remains is much more apparent when the bones are found in the context of cauldrons and altars. The artifacts have specific meanings in the rituals of Santería and spells of Palo Mayombe. When remains have been discarded, residual artifacts and other associated sacred objects, like beaded necklaces, support the assessment of ritual remains. Following these ritual beliefs, if a priest dies, the ritual paraphernalia may be discarded in cemeteries, along riverbanks, or in water (Pokines 2015b).

Trophy Remains

"Trophy" remains most often include skulls, crania only, and occasionally other skeletal elements retained by individuals as souvenirs from wartime contexts. Most often, trophy cases are turned over to a medical examiner's/coroner's office or seized by law enforcement, who in turn request a forensic anthropological analysis to determine medicolegal significance (Yucha et al. 2017). In many instances, little to no contextual information is available, including the original provenience of the remains. In some instances, however, trophy remains are accompanied by general information, such as the location where a veteran served during wartime, or letters, journals, and oral history information in the possession of family members. Some veterans have also played a role in repatriating remains that they removed from conflict areas, especially to Japan following WWII (Harrison 2006, 2008). Provenience information, when it is available, is often vague, and many trophy cases have a complex provenance involving many different individuals, making tracking difficult if not impossible (Huffer and Chappell 2014; Seidemann et al. 2009; Steadman 2009). Forensic anthropologists should be familiar with the taphonomic patterns commonly found on trophy remains to aid in determining medicolegal significance (Pokines 2018).

Yucha et al. (2017) examined the biological profiles and taphonomic characteristics of 14 trophy skull cases in detail, and these were compared with 10 previously published cases (Bass 1983; Sledzik and Ousley 1991; Taylor et al. 1984; Willey and Leach 2009). The combined taphonomic results are presented below.

History of Trophy-Taking

Evidence of trophy-taking of human remains is well documented at several prehistoric archaeological sites (Andrushko et al. 2005, 2010; Bartelink et al. 2014; Browne et al. 1993; Chacon and Dye 2007; Eerkens et al. 2017; Finucane 2008; Santana et al. 2012; Seeman 1988; Tung 2008; Verano 2003), although more recent examples can be found at the eighteenth-century Fort William Henry (Liston and Baker 1996) and among modern traditional societies and tribes (Okumura and Siew 2013; Ross-Stallings 2007). Most often these findings are classified as trophy remains, reflecting their association with interpersonal violence; however, some cases reflect ancestor veneration rather than the taking of trophies of enemies. In general, these examples are easily recognized as archaeological in origin and would rarely fall within the purview of the medicolegal system. Most trophy remains cases in the USA derive from WWII (Fahey 1963; Fussell 1989; Sledge 1981) and the Vietnam war, representing usually individuals of Japanese and Southeast Asian ancestry, respectively (Sledzik and Ousley 1991:520). A common misconception is that all trophy remains (trophy skulls in particular) reflect the removal of body parts of individuals killed in wartime by soldiers.

In many instances, however, remains were collected from battlefield contexts opportunistically by military personnel or from cemetery sites, reflecting a more passive collection strategy (Sledzik and Ousley 1991). In fewer cases, trophies were removed from fallen enemies by those more directly involved in the battle or confrontation (Harrison 2006). Assessment of taphonomic effects on remains can be helpful for recognizing trophy remains that were most likely obtained from decomposed or skeletonized remains.

Given the opportunistic collecting strategy involved with many trophy cases described in the literature, the term "souvenirs" is sometimes a more appropriate descriptor. Previous studies of "trophy" skulls from wartime contexts found more evidence to suggest opportunistic collecting practices than for removal of body parts from slain victims, with several cases likely derived from buried and other non-combatant contexts (Mr. Brian Spatola, Collections Manager, National Museum of Health and Medicine, pers. comm.; Yucha et al. 2017). Despite the ambiguity of classifying these all as "trophies", this terminology has been retained. Given that any collection of human remains from an enemy nation may be used for display and bravado by the collector, i.e., while not a true trophy, it was presented as such. This is supported by a previous study of Vietnamese trophy skulls confiscated by US servicemembers, where postmortem evidence for display included presence of graffiti, candle wax, and mounting damage (Sledzik and Ousley 1991). In some instances, stories on trophy remains related to friends and relatives were embellished and inconsistent with the taphonomic histories of the remains (Malone 2004). Although the collecting of trophy remains was strongly discouraged by the military, the practice was widespread, especially during WWII (Fahey 1963; Fussell 1989; Sledge 1981) and the Vietnam conflict. The popularity of this practice during WWII can best be illustrated by *Life* magazine's "Picture of the Week" for 22 May 1944 (p. 35), which depicts a young woman gazing at a Japanese skull sent to her by her boyfriend with the following description:

> When he said goodby [*sic*] two years ago to Natalie Nickerson, 20, a war worker of Phoenix, Ariz., a big, handsome Navy lieutenant promised her a Jap. Last week Natalie received a human skull, autographed by her lieutenant and 13 friends, and inscribed: "This is a good Jap—a dead one picked up on the New Guinea beach." Natalie, surprised at the gift, named it Tojo. The armed forces disapprove strongly of this sort of thing.

After seeing the image, Army's Judge Advocate General, Major General Myron C. Cramer, sent a memorandum to the War Department stating that the collection of war trophies violated the 1929 Geneva Convention statement on the ill-treatment of the dead or injured (Weingartner 1992). Despite condemnation of the practice, collection of trophy remains continued through the Vietnam conflict, albeit in lower numbers due to stricter custom inspections (Sledzik and Ousley 1991).

Skeletal Characteristics

Of the total 24 trophy skulls, five cases were represented by a partial cranium only, 12 by a cranium only, six by a skull, and one by a skull with associated cervical vertebrae (Yucha et al. 2017) (Table 8.3). One skull case had a mandible that had an unclear association with the cranium and may represent two different individuals. Postmortem tooth loss of anterior teeth was common, although some remains were also missing posterior teeth. All cases were estimated to be male or probable male. Age estimates of the 24 cases provided

Table 8.3 **Skeletal Inventory of Trophy Cases (n = 24)**

Skeletal Inventory	n =	%
Partial cranium only	5	20.8
Cranium only*	12	50.0
Skull	6	25.0
Skull and cervical vertebrae	1	4.2

Source: Yucha et al. (2017); used with permission, John Wiley and Sons.

* Cranium CIL-5 or CIL-6 may be associated with a mandible that was received with them.

age ranges between 15–40 years based on cranial suture obliteration and dental aging. As expected, craniometric analyses classified the cranial remains as likely Asian in origin, with some cases classified closest to Japanese or Vietnamese. It is important to note that trophy remains recovered from WWII contexts, even known battlefields, may not be Japanese, given that Korean, Okinawan, and Taiwanese individuals were conscripted or coerced into serving in the Japanese military (Breen 2004, 2007; Nelson 2003; O'Dwyer 2010; Shibuichi 2005).

Taphonomic Characteristics of Trophy Skulls

Yucha et al. (2017) outlined three taphonomic categories important for analyzing trophy skulls, including: (1) the original acquisition, (2) ornamental alteration, and (3) curation damage, i.e., taphonomic effects caused by storage, display, or repetitive handling. These categories acknowledge that taphonomic effects on trophy skulls can occur on a continuum from the time of original acquisition to the time that the remains are examined.

Taphonomic Characteristics Related to Original Acquisition

Certain taphonomic effects provided evidence indicating if the remains were fresh or decomposed versus completely skeletonized at the time of acquisition, as well as a relative sequence of events for the alterations (Table 8.4). These events span the death of the individual, through any period of decomposition and environmental exposure and through the processing of the remains to remove remaining soft tissue.

Perimortem Trauma: Perimortem (i.e., wet-bone) trauma is a common observation on trophy skulls and presumably reflects injuries sustained in battle. Eight of the 24 trophy skulls (33.3%) showed evidence of perimortem trauma (Figures 8.10 and 8.11), including gunshot wounds, blunt force injuries, or a combination of the two. Absence of trauma, however, should not be used to exclude a skull from having a trophy origin.

Postmortem Environmental Exposure: Certain taphonomic modifications found on suspected trophy remains may signify environmental exposure, suggesting that collection came when remains were decomposed or skeletonized. Examples of environmental exposure include rodent gnawing, carnivore scavenging, soil staining, residual sediment, plant rootlets, insect casings, wasp nests, and sun bleaching/weathering (Chapters 5, 9, 11, and 12). Evidence of postmortem environmental exposure was identified in seven cases (29.2%), including two cases of rodent dry-bone gnawing, five cases of soil staining or residual soil particles present due to prolonged contact with the ground, one case with plant rootlets and insect casings, and three cases with sun bleaching (one of which also

Table 8.4 Summary of Taphonomic Characteristics of Trophy Cases (n = 24)

Characteristic	n =	%	Comments
Taphonomic Characteristics Related to Original Acquisition and Preparation			
Perimortem trauma	8	33.3	
Previous environmental exposure	7	29.2	
Overall preservation	N/A		Generally good to excellent; none noted to have a greasy texture, and most examined noted to have retained their organic sheen
Cleaned/prepared	24	100.0	
Adhering soft tissue	1	4.2	
Micro-abrasions from scrubbing	3	12.5	
Mineral (hard water) scale	1	4.2	
Thermal damage	5	20.8	
Bleaching from preparation	0	0.0	
Taphonomic Characteristics Related to Ornamental Display			
Writing	6	25.0	One case had anatomical details painted
Other paint/ink/pencil	10	41.7	
Coating	5	20.8	
Enlarged foramen magnum	5	20.8	
Display mounting damage	5	20.8	
Other bone reshaping	2	8.3	One case had teeth that were filed flat; another had bone sections removed to show internal anatomical detail
Metallic staining	3	12.5	
Candle wax residue	5	20.8	
Smoke residue	5	20.8	
Taphonomic Characteristics Related to Curation			
Handling damage	20	83.3	
Shelf wear	6	26.1	% = 6 of 23 cases (one case had the entire inferior aspect fragmented)
Patina/handling polish	6	25.0	
Adhesive/reconstruction	4	16.7	
“Attic” dust	5	20.8	
Color/staining	N/A		Variable, from natural bone color to shades of medium or darker brown; multiple cases noted to have a mottled brown color
Later insect activity	1	4.2	
Sediments from curation	3	12.5	

Source: Yucha et al. (2017); used with permission, John Wiley and Sons.

had adhering insect casings, one with adhering sediment and insect casings, and one with adhering sediment and mud patches from possible wasp nests).

Overall Preservation: All 24 trophy skulls were well-preserved and dry, and only three showed a high degree of degradation associated with postmortem breakage and erosion. Postmortem damage was common on thinner areas of the skull, such as the eye orbits,

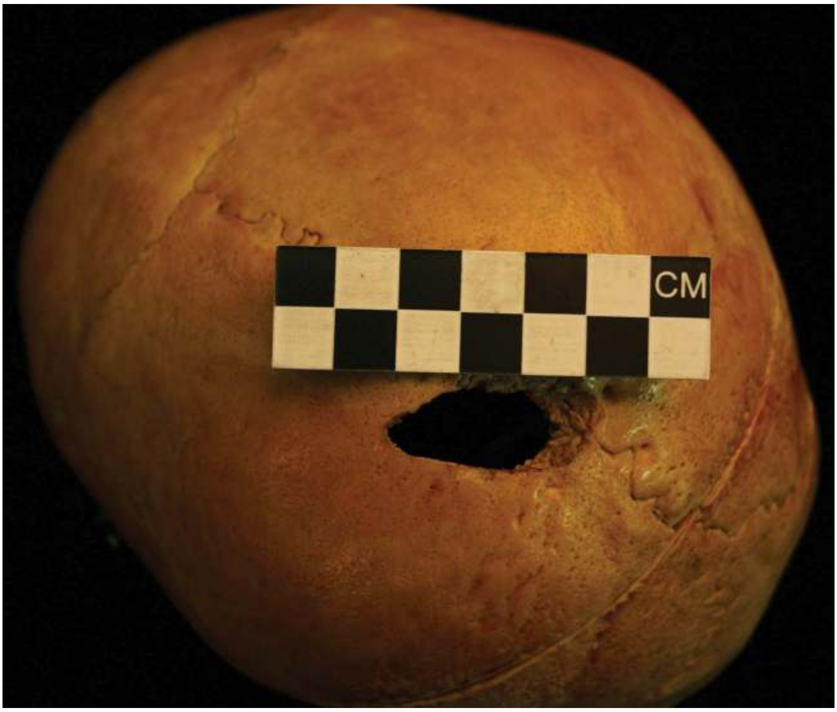

Figure 8.10 Gunshot wound (keyhole defect) on the vault of CSU-3. The scale is in cm. (From Yucha et al. 2017; used with permission, John Wiley and Sons.)

interior nasal structures, and styloid processes. Two cases lacked a face, one of which may be associated with perimortem blunt force trauma. One case was shallowly buried for 40 years post-acquisition, which resulted in a high level of fragmentation and degradation. All but one case retained an organic sheen of the external cortical surface.

Cleaned/Prepared: All 24 trophy skulls showed evidence of having been cleaned and prepared and some showed processing damage. Only one case retained a small amount of desiccated soft tissue (Figure 8.12), which was observed on the exterior vault, the basicranium, in some internal spaces of the skull, and around the alveolar bone.

Micro-abrasions: Trophy skulls from the WWII era were processed by boiling, treatment with lye, or by being dragged in nets behind ships in the Pacific Ocean (Iserson 2001; Scott 1962). Three of the trophy skulls (12.5%) showed evidence of micro-abrasions, which likely occurred when the remains were scrubbed to remove soft tissues (Figure 8.13). In these cases, the micro-abrasions are the same color as the adjacent bone, indicating that the marks were not made more recently (Chapter 20). These three cases also lacked perimortem trauma and evidence of prolonged postmortem environmental exposure. Micro-abrasions can also occur on skeletal remains exposed to fluvial or aquatic environments, when they come into contact with rocks, sediments, and other rough surfaces. Those abrasions are fainter in appearance and have a more polished appearance than micro-abrasions due to processing (Chapters 6 and 7).

Mineral (Hard Water) Scale: Calcium carbonate ($CaCO_3$) or other pale mineral scale deposits can be observed on trophy remains processed through boiling. One of the trophy skulls (4.2%) has white stains on the posterior/inferior vault (Figure 8.14), likely from

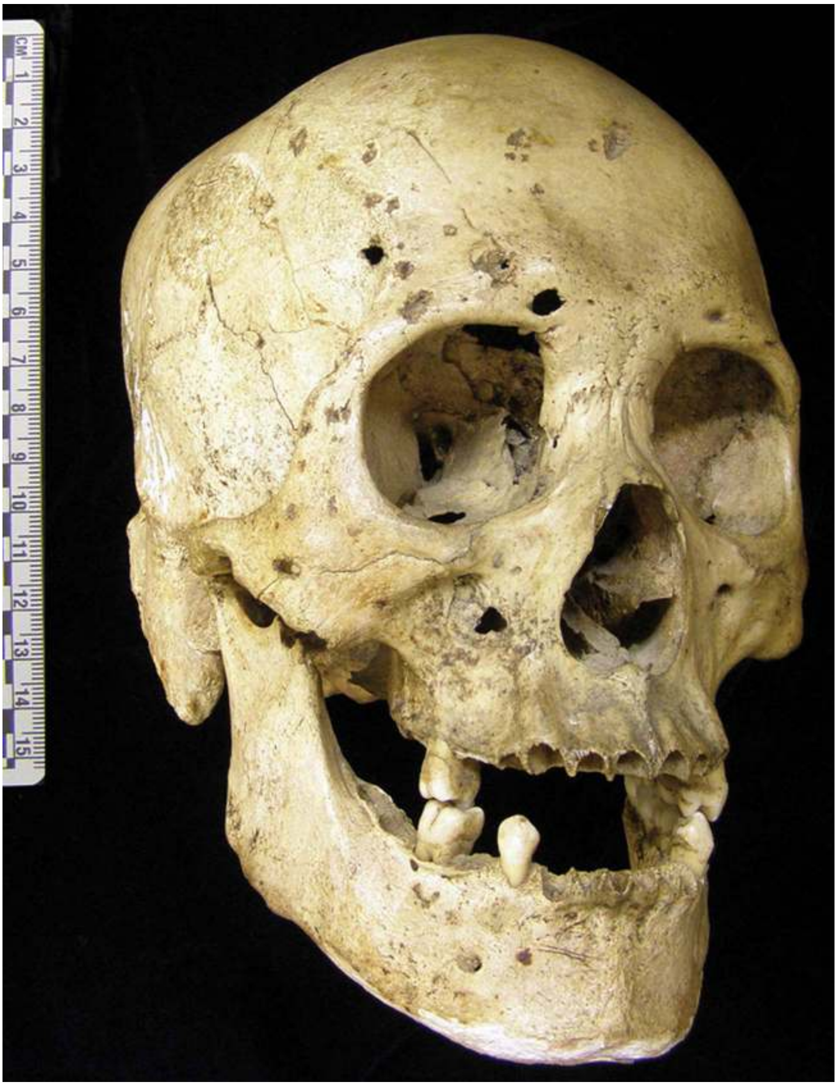

Figure 8.11 Diffuse ballistic trauma from shrapnel impacts (arrows) on the right side of CIL-3. (From Yucha et al. 2017:1270; used with permission, John Wiley and Sons; original permission from CIL. Image by J. Yucha.)

dissolved minerals in water used as part of the boiling process. These modifications can be differentiated from mineral scale that may form within coffins infiltrated with water, which tend to leave a distinct border along the usual water line (Chapter 5).

Thermal Damage: Five of the trophy skulls cases (20.8%) showed evidence of thermal damage, four of which showed evidence of localized damage (i.e., scorching) on the inferior cranium (Yucha et al. 2017: Figure 9). This damage is likely due to processing remains in the field, where trophy skulls were macerated using fuel drums or large metal vats (Fussell 1988). One case exhibited localized thermal damage to the right occipital condyle, possibly due to the use of the skull as an ashtray (Taylor et al. 1984:1259), but this localized damage could be due to skeletal processing.

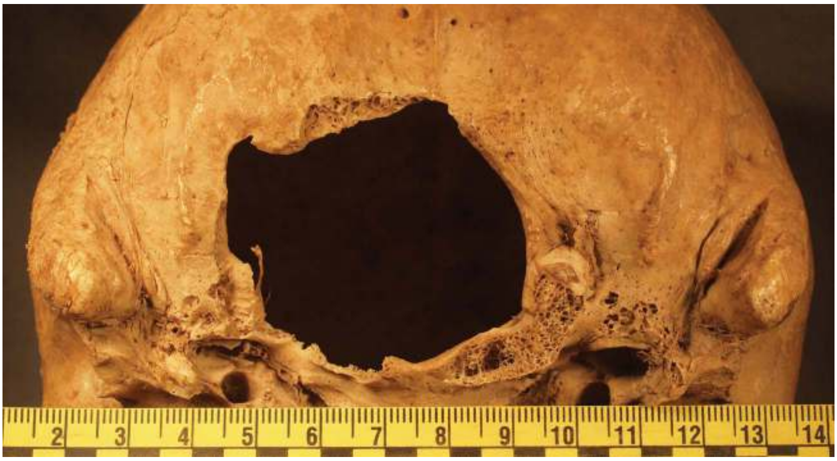

Figure 8.12 Desiccated soft tissue on OCME-MA-2 around left mastoid process and viewed within foramen magnum OCME-MA-2. Note also that the foramen magnum was enlarged by fracturing away the margin. The scale is in cm.

Figure 8.13 Micro-abrasions from scrubbing preparation around the right asterion of CIL-2. (From Yucha et al. 2017:1273; used with permission, John Wiley and Sons; original permission from CIL. Image by J. Yucha.)

Taphonomic Characteristics Related to Ornamental Display

The second category of effects often found on trophy skulls is ornamental alteration (Table 8.4). Most often, these involve deliberate alterations to skulls related to display, although unintentional actions may have affected them as well.

Writing: Six of the 24 trophy skulls (25.0%) exhibited evidence of writing (Figure 8.15). Most often, this involves people's names, locations, dates, or racial slurs (Sledzik and Ousley

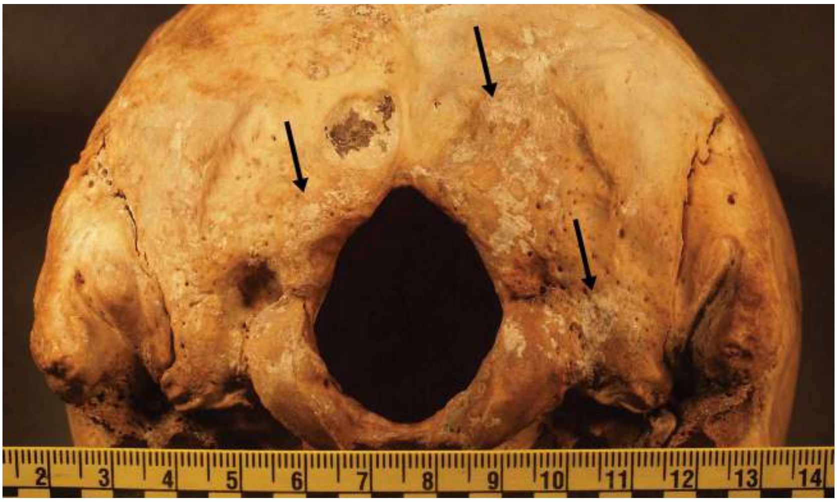

Figure 8.14 White build-up consistent with $CaCO_3$ mineral scale (arrows) from cooking processing on the posterior of OCME-MA-1a. The scale is in cm.

1991). This information can help in establishing the provenience of remains, including location acquired, date acquired, and the individual(s) who took initial possession of the remains. As discussed above, writing also may be found on anatomical teaching specimens, but some trophy skulls have also been repurposed as teaching specimens (Figure 8.16).

Other Markings: Ten of the trophy skulls (41.7%) exhibited paint, ink, or pencil marks. These may be intentional in nature (e.g., painted skulls) or may have been accidental marks from crayon, ink, paint, or even rust. Three of the ten cases involved the use of paint as a cosmetic enhancement, including paint in the posterior eye orbits, painted eyebrows and mustache, and painted teeth. Two other skulls were painted all over.

Coating: Five of the trophy skulls (20.8%) displayed evidence of a protective coating applied to the external surface. These are clear coatings made of varnish or similar substances that provide a protective sheen to the skull.

Enlarged Foramen Magnum: Five of the trophy skulls (20.8%) had an enlarged foramen magnum or showed an abandoned attempt to widen or modify the foramen magnum (Figure 8.12). This may have been done to insert a candle or light into the cranial base for display purposes (Bass 1983) or to affix the cranium to a post.

Display Mounting Damage: Five trophy skulls (20.8%) displayed damage suggestive of mounting, including holes drilled through the mastoid processes and mandibular condyles to articulate the mandible to the cranium or at bregma, likely to suspend the cranium from a wire or string (Sledzik and Ousley 1991). One case was mounted onto a wooden stand with wires, with drill holes in the mastoid processes and the occipital bone. Another skull had three defects into the surface, likely from a display stand.

Other Bone or Tooth Modification: One of the trophy skulls showed evidence of filed teeth resulting in extreme artificial wear of the occlusal surface. This may have been done to make the teeth fit together more evenly or for display purposes. A second trophy skull had multiple windows cut into the bone to expose internal structures, a sectioned calotte, and metal hardware, indicating that it was repurposed as a teaching specimen.

Metallic Staining: Three trophy skulls (12.5%) showed evidence of metallic staining, two of which were consistent with rust staining and one with brass or copper.

Figure 8.15 View of some of the extensive writing on CIL-1. (From Yucha et al. 2017:1268; used with permission, John Wiley and Sons; original permission from CIL. Image by P. Emanovsky.)

Candle-Related Alterations: Five trophy skulls (20.8%) exhibited evidence of melted wax, including spots, drips, or pools (see "Anatomical Remains" section, above). These modifications usually reflect the use of candles to illuminate the skull from inside or to affix a candle to the top of the skull as a candle holder (Sledzik and Ousley 1991). Smoke residue was also present in five cases, most often on the endocranial surface, within the nasal aperture, and on the posterior palate and lacrimals.

Taphonomic Characteristics Related to Curation

The final category of taphonomic effects relates to curation (Table 8.4), and these alterations often overlap with those observed on former anatomical specimens (see "Anatomical Remains" section, above).

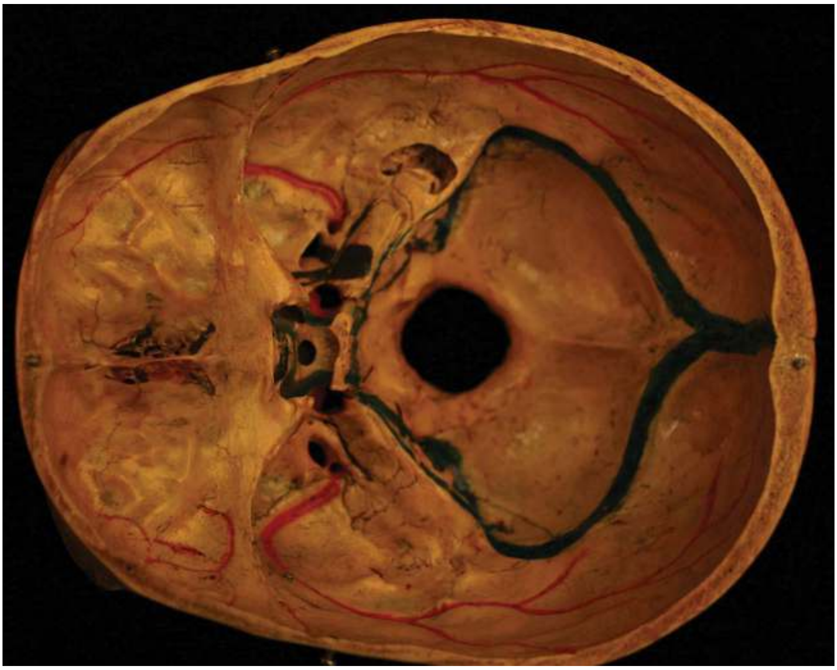

Figure 8.16 Extensive anatomical notation on the endocranium of CSU-2; note the even sectioning of the vault.

Handling Damage: Twenty trophy skulls (83.3%) had probable handling damage, most often to the fragile bones of the face, including the eye orbits, inferior nasals, alveolar bone, and zygomatics, and the styloid processes. Damage to the eye orbits may be intentional (e.g., skulls illuminated with candles or lights) or unintentional damage during processing or handling.

Shelf Wear: Six trophy skulls (26.1%) of 23 cases that had an intact inferior portion exhibited shelf wear, unintentional handling damage caused by the cranial base being in repeated contact with a hard surface (see “Anatomical Remains” section, above). Shelf wear was most often observed on the occipital condyles, mastoid processes, and inferior mandibular margin, and may be associated with erosion and flaking of the outer cortical bone.

Patina/Handling Polish: Patina (see “Anatomical Remains” section, above) or handling polish was present on six trophy skulls (25.0%). It is produced by a combination of dust, dirt, and oils from human skin along with repeated handling (Pokines 2015a).

Adhesive/Reconstruction: Four trophy skulls (16.7%) had evidence of adhesive, which ranged from glue used to hold teeth within the alveolar bone, tape residue on a mandible and maxilla, and the use of a gray clay, putty, or caulking compound on an occipital bone and adjacent parts of the skull. Adhesives may be used to reconstruct bones or for cosmetic display purposes.

Dust: Five trophy skulls (20.8%) showed evidence of a substantial coating of (“attic”) dust, which is most easily observed endocranially and inside the eye orbits and nasal aperture.

Color/Staining: The color of the trophy cases ranged from close to natural bone color (pale beige) to darker brown. Sun bleaching was noted on portions of three cases that were otherwise natural bone color. Three cases were uniformly brown, seven cases had variable brown coloring, and one (Sledzik and Ousley 1991) was dark brown.

Later Insect Activity: Insect activity was present on one trophy skull (4.2%), and likely occurred during storage as opposed to environmental exposure. The one specimen had dead spiders and webs located in its interior spaces.

Sediments: Non-dust sediment adhesion was rare in the sample. Two cases had sediments from during the later curation period, and one additional case had sediments all over, since it had been buried for over 40 years in a yard. Two other cases had non-curational sediments: one case had sediments likely derived from its proximate discovery on the ground surface, and one case had sediments on the frontal bone endocranial surface (Sledzik and Ousley 1991) that could have come from earlier environmental exposure.

Conclusions

When human remains are found among a person's belongings, or out of context, analysis of the taphonomic effects is important in determining forensic significance and functional categorization of the remains, as discussed here for cases with anatomical, ritual, and trophy origins in the USA. Forensic anthropologists are frequently called upon to determine whether unidentified human remains are forensically significant (Pokines 2018, 2020; Schultz 2012), and, in turn, their role is to be able to recognize the potentially unique suite of taphonomic effects found in each of these types of cases in order to accurately classify the remains. A review of past literature concerning the taphonomic signatures of these case types often focuses solely on individual case reports.

Once a case is determined to lack forensic significance, aspects of an anthropological analysis may be underreported or omitted, thus possibly skewing some of the results presented here for cases that could not be directly analyzed by the authors. It is important to note, however, that while remains classified as anatomical or ritual are not always considered to be forensically significant because no cause and manner of death will be determined, these types of remains may still be of legal interest depending on how the material was procured (Komar and Buikstra 2008). Variations from the taphonomic characteristics reported here are stressed, as the limits of human alterations to bone are conceivably endless. There are a number of instances where human remains are repurposed for reasons not relating to anatomical display and education, or for religious and ritual uses; however, the discussion of the myriad of alterations to human skeletal material is beyond the scope of this chapter.

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References

Andrushko, V. A., K. A. S. Latham, D. L. Grady, A. G. Pastron, and P. L. Walker (2005) Bioarchaeological evidence for trophy-taking in prehistoric Central California. *American Journal of Physical Anthropology* 127(4):375–384.

Andrushko, V. A., A. W. Schwitalla, and P. L. Walker (2010) Trophy-taking and dismemberment as warfare strategies in prehistoric Central California. *American Journal of Physical Anthropology* 141(1):83–96.

Anyanwu, G. E., O. O. Udemezue, and E. N. Obikili (2011) Dark age of sourcing cadavers in developing countries: A Nigerian survey. *Clinical Anatomy* 24(7):831–836.

B for Bones (2018) About Us. Electronic document, https://bforbones.com/about-us/, accessed 31 January 2021.

Backwell, L., and F. d'Errico (2003) Additional evidence on the early hominid bone tools from Swartkrans with reference to spatial distribution of lithic and organic artefacts. *South African Journal of Science* 99(5):259–267.

Bartelink, E. J., V. A. Andrushko, V. Bellifemine, I. Nechayev, and R. Jurmain (2014) Violence and warfare in the prehistoric San Francisco Bay area, California: Regional and temporal variations in conflict. In *The Routledge Handbook of the Bioarchaeology of Human Conflict* ed. by C. Knüsel and M. Smith, pp. 285–308. Taylor and Francis, Oxford.

Bass, W. M. (1983) The occurrence of Japanese trophy skulls in the United States. *Journal of Forensic Sciences* 28(3):800–803.

Becton, Dickinson and Company (2021) (Home page.) Electronic document, https://www.bd.com/en-us, accessed 31 January 2021.

Bernstein, R. E. (2018) The Skeleton in My Closet. Electronic document, https://www.nytimes.com/2018/05/18/well/family/the-skeleton-in-my-closet.html, accessed 31 January 2021.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1991) Recognition of cemetery remains in the forensic setting. *Journal of Forensic Sciences* 36(1):230–237.

Blake, J. B. (1955) The development of American anatomy acts. *Journal of Medical Education* 30(8):431–439.

Blakely, R. L., and J. M. Harrington (1997) Grave consequences: The opportunistic procurement of cadavers at the Medical College of Georgia. In *Bones in the Basement: Postmortem Racism in Nineteenth-Century Medical Training* ed. by R. L. Blakely and J. M. Harrington, pp. 162–183. Smithsonian Institution Press, Washington, DC.

Bonnichsen, R., and M. H. Sorg (eds.) (1989) *Bone Modification*. Center for the Study of the First Americans, Orono, ME.

Brain, C. K. (1981) *The Hunters or the Hunted? An Introduction to African Cave Taphonomy*. University of Chicago Press, Chicago.

Brandon, G. (1993) *Santeria from Africa to the New World: The Dead Sell Memories*. Indiana University Press, Bloomington, IN.

Breen, J. (2004) The dead and the living in the land of peace: A sociology of the Yasukuni Shrine. *Mortality* 9(1):76–93.

Breen, J., ed. (2007) *Yasukuni, the War Dead and the Struggle for Japan's Past*. Hurst, London.

Breneman, J. C. (1993) *The Stryker Story: Homer's Iliad*. Paul Schubert and Associates, Kalamazoo, MI.

Browne, D. M., H. Silverman, and R. García (1993) A cache of 48 Nasca trophy heads from Cerro Carapo, Peru. *Latin American Antiquity* 4(3):274–294.

Buikstra, J. E., and D. H. Ubelaker (1994) *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archeological Survey Research Report No. 44, Fayetteville, AR.

Carney, S. (2007) Inside India's Underground Trade in Human Remains. November 2007. Electronic document, https://www.wired.com/2007/11/ff-bones/, accessed 31 January 2021.

Chacon, R. J., and D. H. Dye, eds. (2007) *The Taking and Displaying of Human Body Parts as Trophies by Amerindians*. Springer, New York.

Crist, T. A., and M. H. Sorg (2016) Renaissance anatomy in the Americas: A bioarchaeological perspective on the earliest skeletal evidence of autopsy in the New World. In *The Bioarchaeology of Dissection and Autopsy in the United States* ed. by K. C. Nystrom, pp. 25–40. Springer, Cham, Switzerland.

Cumback, K. (2018) The ghoulish trade in human remains. *Michigan State International Law Review* 26(2):336–372.

Davidson, J. M. (2007) "Resurrection Men" in Dallas: The illegal use of black bodies as medical cadavers. *International Journal of Historical Archaeology* 11(3):193–220.

Davis, S. (2015) Meet the Living People Who Collect Dead Human Remains. Electronic document, www.vice.com/en_us/article/wd7jd5/meet-the-living-people-who-collect-human-remains-713, accessed 21 January 2021.

De La Torre, M. A. (2004) *Santería: The Beliefs and Rituals of a Growing Religion in America*. Wm. B. Eerdmans, Grand Rapids, MI.

Eerkens, J. W., E. J. Bartelink, L. Brink, R. Fitzgerald, R. Garibay, G. A. Jorgenson, and R. S. Wiberg (2017) Trophy heads or ancestor veneration? A stable isotope perspective on disassociated and modified crania in central California. *American Antiquity* 81(1):114–131.

Fahey, J. J. (1963) *Pacific War Diary*. Houghton Mifflin, Boston.

Fenton, T. W., W. H. Birkby, and J. Cornelison (2003) A fast and safe non-bleaching method for forensic skeletal preparation. *Journal of Forensic Sciences* 48(1):274–276.

Fineman, M. (1991) Changing Lifestyles: Living off the Dead Is a Dying Trade in Calcutta. Electronic document, http://articles.latimes.com/1991-02-19/news/wr-1711_1_skeleton-calcutta-merchant, accessed 31 January 2021.

Finucane, B. C. (2008) Trophy heads from Nawinpukio, Perú: Physical and chemical analysis of Huarpa-era modified human remains. *American Journal of Physical Anthropology* 135(1):75–84.

Fussell, P. (1988) *Thank God for the Atom Bomb and Other Essays*. Summit Books, New York.

Fussell, P. (1989) *Wartime: Understanding and Behavior in the Second World War*. Oxford University Press, New York.

Gill, J. R., C. W. Rainwater, and B. J. Adams (2009) Santeria and Palo Mayombe: Skulls, mercury, and artifacts. *Journal of Forensic Sciences* 54(6):1458–1462.

González-Wippler, M. (1973) *African Magic in Latin America: Santería*. Julian Press, New York.

González-Wippler, M. (1989) *Santería: The Religion*. Harmony Books, New York.

Halling, C. L., and R. M. Seidemann (2016) They sell skulls online?! A review of internet sales of human skulls on eBay and the laws in place to restrict sales. *Journal of Forensic Sciences* 61(5):1322–1326.

Halperin, E. C. (2007) The poor, the Black, and the marginalized as the source of cadavers in United States anatomical education. *Clinical Anatomy* 20(5):489–495.

Hansen, J. V. (1996) Resurrecting death: Anatomical art in the cabinet of Dr. Frederik Ruysch. *The Art Bulletin* 78(4):663–679.

Harrison, S. (2006) Skull trophies of the Pacific War: Transgressive objects of remembrance. *Journal of the Royal Anthropological Institute (New Series)* 12(4):817–836.

Harrison, S. (2008) War mementos and the souls of missing soldiers: Returning effects of the battlefield dead. *Journal of the Royal Anthropological Institute (New Series)* 14(4):774–790.

Hefner, J. T., B. F. Spatola, N. V. Passalacqua, and T. P. Gocha (2016) Beyond taphonomy: Exploring craniometric variation among anatomical material. *Journal of Forensic Sciences* 61(6):1440–1449.

Hildebrandt, S. (2008) Capital punishment and anatomy: History and ethics of an ongoing association. *Clinical Anatomy* 21(1):5–14.

Hodge, C. J. (2013) Non-bodies of knowledge: Anatomized remains from the Holden Chapel Collection, Harvard University. *Journal of Social Archaeology* 13(1):122–149.

Hong Kong Blue Bay (2021) (Home page.) Electronic document, https://hkbluebay.en.ec21.com/, accessed 31 January 2021.

Huffer, D., and D. Chappell (2014) The mainly nameless and faceless dead: An exploratory study of the illicit traffic in archaeological and ethnographic human remains. *Crime, Law and Social Change* 62(2):131–153.

Hugo, K. (2016) Human Skulls Are Being Sold Online, But Is It Legal? Electronic document, http://news.nationalgeographic.com/2016/08/human-skulls-sale-legal-ebay-forensics-science/, accessed 15 August 2020.

Humphrey, D. C. (1973) Dissection and discrimination: The social origins of cadavers in America, 1760-1915. *Bulletin of the New York Academy of Medicine* 49(9):819–827.

Hutt, S., and J. Riddle (2007) The law of human remains and burials. In *Human Remains: Guide for Museums and Academic Institutions* ed. by V. Cassman, N. Odegaard, and J. F. Powell, pp. 223–243. AltaMira Press, Plymouth, UK.

Huxley, A. K., and M. Finnegan (2004) Human remains sold to the highest bidder! A snapshot of the buying and selling of human skeletal remains on eBay, an internet auction site. *Journal of Forensic Sciences* 49(1):17–20.

Iserson, K. V. (2001) *Death to Dust: What Happens to Dead Bodies?* (2nd ed.). Galen Press, Tucson, AZ.

Jones, D. G., and M. I. Whitaker (2012) Anatomy's use of unclaimed bodies: Reasons against continued dependence on an ethically dubious practice. *Clinical Anatomy* 25(2):246–254.

Kamath, V., S. Bhat, M. Asif, and R. Avadhani (2016) Anatomy museums of southern India and medical education: An original research. *Indian Journal of Clinical Anatomy and Physiology* 3(1):45–49.

Komar, D. A., and J. E. Buikstra (2008) *Forensic Anthropology: Contemporary Theory and Practice*. Oxford University Press, New York.

Lesnik, J. J. (2011) Bone tool texture analysis and the role of termites in the diet of South African hominids. *PaleoAnthropology* 2011:268–281. DOI: 10.4207/PA.2011.ART57.

Liston, M. A, and B. J. Baker (1996) Reconstructing the massacre at Fort William Henry, New York. *International Journal of Osteoarchaeology* 6:28–41.

Louisiana State Senate (2016) Chapter 21-C of Title 25, Louisiana Human Remains Protection and Control Act. Electronic document, http://www.legis.la.gov/legis/ViewDocument.aspx?d=1012714, accessed 9 January 2021.

MacGregor, A. (1985) *Bone, Antler, Ivory & Horn: The Technology of Skeletal Materials since the Roman Period*. Barnes and Noble, London.

Malone, P. (2004) Unknown soldier's remains home at last. *The Pueblo Chieftain* 17 May, A10.

Mann, R. W., W. M. Bass, and L. Meadows (1990) Time since death and decomposition of the human body: Variables and observations in case and experimental field studies. *Journal of Forensic Sciences* 35(1):103–111.

Mann, R. W., D. W. Owsley, and P. A. Shackel (1991) A reconstruction of 19th-century surgical techniques: Bones in Dr. Thompson's privy. *Historical Archaeology* 25(1):106–112.

Marsh, T. D. (2012) Rethinking Laws Permitting the Sales of Human Remains. Electronic https://www.huffpost.com/entry/laws-permitting-human-remains_b_1769082?utm_hp_ref=fb&src=sp&comm_ref=false, accessed 31 January 2021.

McFarlin, S. C., and L. E. Wineski (1997) The cutting edge: Experimental anatomy and the reconstruction of the nineteenth-century dissection techniques. In *Bones in the Basement: Postmortem Racism in Nineteenth-Century Medical Training* ed. by R. L. Blakely and J. M. Harrington, pp. 107–161. Smithsonian Institution Press, Washington, DC.

Meiwo Science (2015) Home Page. Electronic document, www.meiwoscience.com/, accessed 31 January 2021.

Mitchell, P. (ed.) (2012) *Anatomical Dissection in Enlightenment England and Beyond: Autopsy, Pathology and Display*. Routledge, London.

Morlan, R. E. (1984) Toward the definition of criteria for the recognition of artificial bone alterations. *Quaternary Research* 22:160–171.

Murrell, N. S. (2009) *Afro-Caribbean Religions: An Introduction to Their Historical, Cultural, and Sacred Traditions*. Temple University Press, Philadelphia.

Nafte, M. (2014) *Trophies and Talismans: The Traffic of Human Remains*. Ph.D. Dissertation, McMaster University, Hamilton, ON.

Nelson, J. (2003) Social memory as ritual practice: Commemorating spirits of the military dead at Yasukuni Shinto Shrine. *Journal of Asian Studies* 62(2):443–467.

Nystrom, K. C. (ed.) (2017) *The Bioarchaeology of Dissection and Autopsy in the United States*. Springer, Cham, Switzerland.

O'Dwyer, S. O. (2010) The Yasukuni Shrine and the competing patriotic pasts of East Asia. *History and Memory* 22(2):147–177.

Ochoa, T. R. (2010) *Society of the Dead: Quita Manaquita and Palo Praise in Cuba*. University of California Press, Berkeley, CA.

Okumura, M., and Y. Y. Siew (2013) An osteological study of trophy heads: Unveiling the headhunting practice in Borneo. *International Journal of Osteoarchaeology* 23:685–697.

Osta International (2019) (Home page.) Electronic document, https://www.osta.ca/, accessed 31 January 2021.

Owsley, D. W. (1995) Contributions of bioarchaeological research to knowledge of nineteenth-century surgery. In *Grave Reflections: Portraying the Past Through Cemetery Studies* ed. by S. R. Saunders and A. Herring, pp. 119–151. Canadian Scholars Press, Toronto, ON.

Pokines, J. T. (2015a) Taphonomic characteristics of former anatomical teaching specimens received at a Medical Examiner's office. *Journal of Forensic Identification* 65(2):173–195.

Pokines, J. T. (2015b) A Santería/Palo Mayombe ritual cauldron containing a human skull and multiple artifacts recovered in western Massachusetts, U.S.A. *Forensic Science International* 248:e1–e7.

Pokines, J. T. (2018) Differential diagnosis of the taphonomic histories of common types of forensic osseous remains. *Journal of Forensic Identification* 68(1):87–145.

Pokines, J. T. (2020) The case of the… cases: The flow of the ordinary into a medical examiner's office. In *Case Studies in Forensic Anthropology: Bonified Skeletons* ed. by H. Garvin and N. Langley, pp. 291–302. CRC Press, Boca Raton, FL.

Pokines, J. T., N. Appel, C. Pollock, C. J. Eck, A. G. Maki, A. S. Joseph, L. Cadwell, and C. D. Young (2017) Anatomical taphonomy at the source: Alterations to a sample of 84 teaching skulls at a medical school. *Journal of Forensic Identification* 67(4):600–632.

Redman, S. J. (2016) *Bone Rooms*. Harvard University Press, Cambridge, MA.

Richardson, R. (2000) *Death, Dissection and the Destitute*. University of Chicago Press, Chicago.

Roach, M. (2003) *Stiff: The Curious Lives of Human Cadavers*. W. W. Norton, New York.

Ross-Stallings, N. A. (2007) Trophy taking in the central and lower Mississippi Valley. In *The Taking and Displaying of Human Body Parts as Trophies by Amerindians* ed. by R. J. Chacon and D. H. Dye, pp. 339–370. Springer, New York.

Santana, J., J. Velasco, J. J. Ibáñez, and F. Braemer (2012) Crania with mutilated facial skeletons: A new ritual treatment in an early Pre-Pottery Neolithic B cranial cache at Tell Qarassa North (South Syria). *American Journal of Physical Anthropology* 149(2):205–216.

Sappol, M. (2002) *A Traffic of Dead Bodies: Anatomy and Embodied Social Identity in Nineteenth-Century America*. Princeton University Press, Princeton, NJ.

Schultz, J. J. (2012) Determining the forensic significance of skeletal remains. In *A Companion to Forensic Anthropology* ed. by D. C. Dirkmaat, pp. 66–84. Wiley-Blackwell, Chichester, UK.

Scott, W. T. (1962) *Collected Poems: 1937-1962*. Macmillan, New York.

Scovil, L. K. (2015) *Market for Death: The Use and Abuse of Cadavers in Nineteenth-Century America*. M.A. Thesis, University of Houston, Houston, TX.

Seeman, M. F. (1988) Ohio Hopewell trophy-skull artifacts as evidence for competition in Middle Woodland societies circa 50 B.C.-A.D. 350. *American Antiquity* 53(3):565–577.

Seidemann, R. M. (2004) Bones of contention: A comparative examination of law governing human remains from archaeological contexts in formerly colonial countries. *Louisiana Law Review* 64(3):546–576.

Seidemann, R. M. (2010) NAGPRA at 20: What have the states done to expand human remains protections? *Museum Anthropology* 33(2):199–209.

Seidemann, R. M., C. M. Stojanowski, and F. J. Rich (2009) The identification of a human skull recovered from an eBay sale. *Journal of Forensic Sciences* 54(6):1247–1253.

Shibuichi, D. (2005) The Yasukuni Shrine dispute and the politics of identity in Japan. *Asian Survey* 45(2):197–215.

Skull Store (2021) About Us. Electronic document, http://www.skullstore.ca/pages/aboutus, accessed 31 January 2021.

Skulls Unlimited International (2021) (Home page.) Electronic document, http://www.skullsunlimited.com/, accessed 31 January 2021.

Sledge, E. B. (1981) *With the Old Breed: At Peleliu and Okinawa*. Presidio Press, New York.

Sledzik, P. S., and M. S. Micozzi (1997) Autopsied, embalmed, and preserved human remains: Distinguishing features in forensic and historic contexts. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 483–496. CRC Press, Boca Raton, FL.

Sledzik, P. S., and S. Ousley (1991) Analysis of six Vietnamese trophy skulls. *Journal of Forensic Sciences* 36(2):520–530.

Snyder, R. G., A. Burdi, and G. Gaul (1975) A rapid technique for preparation of human fetal and adult skeletal material. *Journal of Forensic Sciences* 20(3):576–580.

Steadman, D. W. (2009) The pawn shop mummified head: Discriminating among forensic, historic, and ancient contexts. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 258–270. Prentice Hall, Upper Saddle River, NJ.

Stephens, B. G. (1979) A simple method for preparing human skeletal material for forensic examination. *Journal of Forensic Sciences* 24(3):660–662.

Stubblefield, P. R. (2011) The anatomical diaspora: Evidence of early American anatomical traditions in North Dakota. *Journal of Forensic Sciences* 56(5):1324–1327.

Taylor, J. V., L. Roh, and A. D. Goldman (1984) Metropolitan Forensic Anthropology Team (MFAT) case studies in identification: 2. Identification of a Vietnamese trophy skull. *Journal of Forensic Sciences* 29(4):1253–1259.

The Bone Room (2019) (Home page.) Electronic document, https://www.boneroom.com/store/c1/Featured_Products.html, accessed 31 January 2021.

Tung, T. A. (2008) Dismembering bodies for display: A bioarchaeological study of trophy heads from the Wari site of Conchopata, Peru. *American Journal of Physical Anthropology* 136(3):294–308.

Verano, J. W. (2003) Mummified trophy heads from Peru: Diagnostic features and medicolegal significance. *Journal of Forensic Sciences* 48(3):525–530.

Walker, P. L. (2008) Bioarchaeological ethics: A historical perspective on the value of human remains. In *Biological Anthropology of the Human Skeleton* (2nd ed.) ed. by M. A. Katzenberg and S. R. Saunders, pp. 3–40. Wiley-Liss, Hoboken, NJ.

Walker, J. E. C., G. N. Rutty, B. Rodgers, and N. W. F. Woodford (2002) How should the chest wall be opened at necropsy? *Journal of Clinical Pathology* 55(1):72–75.

Weingartner, J. J. (1992) Trophies of war: U.S. troops and the mutilation of Japanese war dead, 1941-1945. *Pacific Historical Review* 61(1):53–67.

Wetli, C. V., and R. Martinez (1981) Forensic sciences aspects of Santeria, a religious cult of African origin. *Journal of Forensic Sciences* 26(3):506–514.

Wetli, C. V., and R. Martinez (1983) Brujeria: Manifestations of Palo Mayombe in South Florida. *Journal of the Florida Medical Association* 70(8):629–634, 634a.

Wienker, C. W., J. E. Wood, and C. A. Diggs (1990) Independent instances of “souvenir” Asian skulls from the Tampa Bay area. *Journal of Forensic Sciences* 35(3):637–643.

Willey, P., P. Gavette, E. J. Bartelink, and C. Milligan (in press) *Bones by the Bay: History, Archaeology, and Bioarchaeology of Nineteenth Century Anatomized Skeletons at Point San Jose, San Francisco*. University Press of Florida, Gainesville, FL.

Willey, P., and P. Leach (2009) The skull on the lawn: Trophies, taphonomy, and forensic anthropology. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 179–189. Prentice Hall, Upper Saddle River, NJ.

Winburn, A. P., R. Martinez, and S. K. Schoff (2017) Afro-Cuban ritual use of human remains: Medicolegal considerations. *Journal of Forensic Identification* 67(1):1–30.

Winburn, A. P., S. K. Schoff, and M. W. Warren (2016) Assemblages of the dead: Interpreting the biocultural and taphonomic signature of Afro-Cuban Palo practice in Florida. *Journal of African Diaspora Archaeology and Heritage* 5(1):1–37.

Young Brothers (2021) (Home page.) Electronic document, https://www.youngbrothers.co.in/, accessed 31 January 2021.

Yucha, J. M., J. T. Pokines, and E. J. Bartelink (2017) A comparative taphonomic analysis of 24 trophy skulls from modern forensic cases. *Journal of Forensic Sciences* 62(5):1266–1278.

Faunal Dispersal, Reconcentration, and Gnawing Damage to Bone in Terrestrial Environments

9

JAMES T. POKINES

Contents

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> Shall in these confines with a monarch's voice
> Cry 'Havoc' and let slip the dogs of war;
> That this foul deed shall smell above the earth
> With carrion men, groaning for burial.
>
> **—William Shakespeare**
> *Julius Caesar,* Act III, Scene 1

Introduction

Humans and their relatives in the family Hominidae have a long history of being eaten by species that have evolved to do precisely that (Brain 1980, 1981; Corbett 1944; Domínguez-Rodrigo 1999; Hart 2002; Hart and Sussman 2008; Kerbis Peterhans 1990; Kerbis Peterhans and Gnoske 2001; Kruuk 2002; Patterson 1996; Payne 1983; Treves and Naughton-Treves 1999; Wroe et al. 2005). This trophic relationship also applies to our extant relatives among the Hominoidea (Boesch 1991; Fay et al. 1995; Galdikas 1978; Kerbis Peterhans et al. 1993) and other large primates (Hart 2002; Pickering and Carlson 2004; Simons 1966). This relationship also extends to remains examined in forensic anthropology (Ubelaker and DeGaglia 2020), since a large number of these hunting/scavenging species coexist with modern humans, despite the generally severe decreases in population sizes and restrictions and fragmentations of territories of the former over the past several 1000 years. A hominid body, whether it was one of our distant ancestors felled by a leopard in East Africa or a recent murder victim dumped into the New England woods, represents an enormous temporary boost in consumable resources for the local ecosystem into which it was introduced. Thousands of vertebrate and invertebrate species have evolved for millennia to exploit those and similar resources as efficiently and fully as possible, or their own survival would not be as secure. In short, a deceased human is nothing new to the many populations of decomposers and consumers that would exploit it. These interactions follow similar patterns with other large mammal carcasses, despite variations in anatomy and body mass.

The interaction with a human cadaver goes beyond consumption of soft tissue: other resources are present, and other interactions occur besides direct consumption. The bones themselves are a valuable resource, especially the large fat reserves contained within the marrow cavities of the long bones of adult mammals and their mineral content. Bones are also transported away from the initial location of body deposition and sometimes reconcentrated in other locations. Bone gnawing therefore is just one component of feeding behavior and must be examined within the larger process of remains utilization. One must also note that it is rare for a set of remains in an outdoor setting to have been scavenged by only one species, so bone alteration and movement are likely amalgams of the behavior of multiple agents. Careful analysis may allow the distinction of these separate taphonomic processes, including in some cases the order in which they occurred.

This chapter covers the typical processes of bone gnawing, dispersal, and, in some cases, reconcentration in terrestrial environments. The taxa discussed in the following text include the terrestrial mammalian fauna most potentially relevant to forensic settings: carnivores, rodents, pigs, and other ungulates. The specific taphonomic effects of sharks are covered in (Chapter 7, this volume), as well as birds (Chapter 16), invertebrates (Chapter 18), and reptiles (Chapter 19).

Reasons for Bone Gnawing, Other Damage, and Dispersal

Bones are gnawed upon for multiple reasons by many common terrestrial taxa. These include, most importantly, the following.

A Byproduct of Predation: The act of capturing and killing prey by a large predator can start the bone damaging process. Often, the more fragile bones are damaged as the predator lands upon the prey, or its teeth or claws are employed in order to kill it. This process is much more damaging in the case of prey smaller than adult humans, such as a canid snatching and crushing the skeleton of a bird or rodent at the moment of capture. In larger prey, the skeleton is often avoided as much as possible at the moment of capture due to the increased difficulty of biting through bony portions. Often, attacks are directed toward the throat or to kill by disembowelment (Kruuk 1972, 2002).

Dismemberment of Prey: The dismemberment of prey during feeding often begins the process of skeletal disarticulation. Bone breakage will likely occur during this process, as limbs are detached for transport away from the place of initial carcass/cadaver deposition, and more fragile elements (particularly among the thoracic area) are broken in order to access their associated soft tissue. The mass of the consuming animal also may break bone, especially in the thoracic cage of the consumed (Berryman 2002).

Associated Exterior Soft Tissue: Damage to skeletons also occurs as the soft tissue is consumed from it, from incidental tooth action of the consuming species (Pobiner 2007; Pobiner et al. 2020). More extensive damage and dismemberment normally follow after this initial phase, where the easier-to-consume soft tissue is attacked first (Blumenschine 1986, 1988). Smaller species, especially rats (*Rattus* spp.) and other omnivorous rodents, also will consume bone as they gnaw through associated soft tissue or to access interior soft tissue.

Marrow and Grease Content of Bones: Bones are a valuable source of fat (Arilla et al. 2020; Brink 1997; Lupo 1998; Madrigal and Holt 2002; Morin 2007; Okarma 1991), which can be a scarce resource among wild animals, especially during the winter months in the temperate and more northern zones and drier months in the subtropical and tropical zones. Marrow fat reserves are often the last to be depleted during times of nutritional stress (Bear 1971; Lochmiller et al. 1985). Humans raised in modern industrial societies are used to consuming farm-raised species specifically bred and fed to encourage an overall fat content not normally encountered among their wild counterparts. A larger component of stored fat among terrestrial wild game therefore is contained within the long bone cavities as opposed to dispersed among the muscle tissue or stored subcutaneously. As a consequence of this anatomical pattern, many species of carnivores have evolved to exploit this resource. These include, to some degree, most large carnivores encountered in North America and Eurasia (including canids, ursids, mustelids, and felids) and especially hyaenids encountered in Africa and Eurasia, which have evolved as the most damaging extant bone gnawers (Becker and Reed 1993; Kerbis Peterhans 1990; Kruuk 1972; Pokines and Kerbis Peterhans 2007; Tanner et al. 2008).

Nutrients from the Mineral Content of the Bones: Bone gnawing supplies minerals (calcium, phosphate, sodium, and potassium) to multiple species, including rodents. Old World porcupines (*Hystrix* spp.), in particular, have been determined experimentally to consume a portion of the bones upon which they gnaw (Duthie and Skinner 1986; Mori et al. 2018), specifically in pursuit of dietary sodium (Roze 2009). Other rodents known to gnaw upon and possibly consume dry bone include pocket gophers (*Geomys* spp.) (Smith 1948) and squirrels (*Sciurus* spp.) (Carlson 1940; Coventry 1940). Multiple ungulate species also are known to practice *osteophagia* (bone consumption) in response to local environmental mineral (likely phosphorus) nutritional deficiencies. These geographically dispersed taxa include sheep (*Ovis aries*) (Brothwell 1976), deer (Cervidae) (Bowyer 1983; Cáceres et al. 2011; Gambín et al. 2017; Kierdorf 1993, 1994; Sutcliffe 1973, 1977), and giraffe (*Giraffa camelopardalis*) (Hutson et al. 2013; Wyatt 1971).

Rodent Incisor Sharpening: Many rodent species also will gnaw upon a variety of available hard substances, including (dry) bone, wood, and in some cases metal (Minetz 2010) and carbonate rocks (Gobetz and Hattin 2002). The presumed reason for this behavior is sharpening and wearing of their continuously growing incisors, although in the case of carbonate rocks, the gnawing also may be in response to dietary deficiency (Gobetz and Hattin 2002). Rodent incisor sharpening also occurs naturally through edge-to-edge incisor contact and also occurs in rodent species that are not known to collect and gnaw bones. Given the over 2200 described species of rodents throughout the world (Wilson and Reeder 2005), research into those that gnaw bone and how they gnaw has barely been touched upon. The great overlap in the size of rodent incisors among species worldwide, and the dental formula common to all rodents of two upper and two lower incisors may reduce the variation in the marks that they produce (Pokines et al. 2017).

Boredom, Especially among Domestic or Zoo Animals: Many studies of zoo, captive, and domesticated animals gnawing upon bones note their greater tendency to damage bone, likely due to the greater amount of time devoted to a single bone combined with a lack of other diversion (Domínguez-Solera and Domínguez-Rodrigo 2009; Haynes 1983; Marean et al. 1992; Pobiner 2007; Willey and Snyder 1989). Excessive gnawing for no clear nutritional benefit is termed the *kennel pattern*. Domestic dogs often are given commercially prepared large leg bone portions (typically cattle bones) to gnaw upon, despite all the easily obtained nutrients already having been removed through cleaning of interior and exterior soft tissues. These bones may receive much more attention than wild-caught or scavenged bones would, again due to their singularity and the increased leisure time among domestic animals. They are also sometimes deliberate objects of play and can receive additional damage in this manner. Highly advanced rounding/polish (Figure 9.1) can develop under these circumstances.

Mechanics of Terrestrial Carnivore Bone Gnawing

The mechanics of terrestrial carnivore bone gnawing differ greatly, for example, from feeding movement and consumption by sharks. While having jaws that can crush down with a large amount of force (Wroe et al. 2005), sharks primarily dismember their prey by shaking their heads laterally, producing a shredding effect with their multiple rows of sharp, serrated, yet relatively fragile teeth (Chapter 7). Bones are not usually crushed as a result of

Figure 9.1 Large mammal long bone rounded and polished through repeated gnawing by a large domestic dog (*Canis familiaris*). The scale is in cm.

this action, which can produce a great deal of dismemberment. Since fish are typical shark prey, their relatively small and fragile bones present much less of an obstacle to dismemberment and consumption. In contrast, large terrestrial mammals, including humans, have stored in their long bones a valuable fat reservoir, and multiple carnivore species have evolved to gnaw upon these bones to get at this resource, or crush smaller bones that are associated with more desirable tissue.

Leverage and Bone Crushing

The main mastication function of a carnivore's maxilla and mandible can be visualized as a (class 3) lever system, with the temporomandibular joint (TMJ) as the fulcrum and the force supplied by the mastication muscles mostly between the fulcrum and the chewed object (Figure 9.2). The least amount of bite force is applied at the incisors, as these are farthest away from the TMJ fulcrum. Halving the distance to the fulcrum roughly doubles the amount of force that can be applied. Since this force increases the farther back that an object can be fit into the mouth, the behavior is often observed among carnivores of turning their heads sideways to gnaw upon a bone with their posterior teeth (premolars and

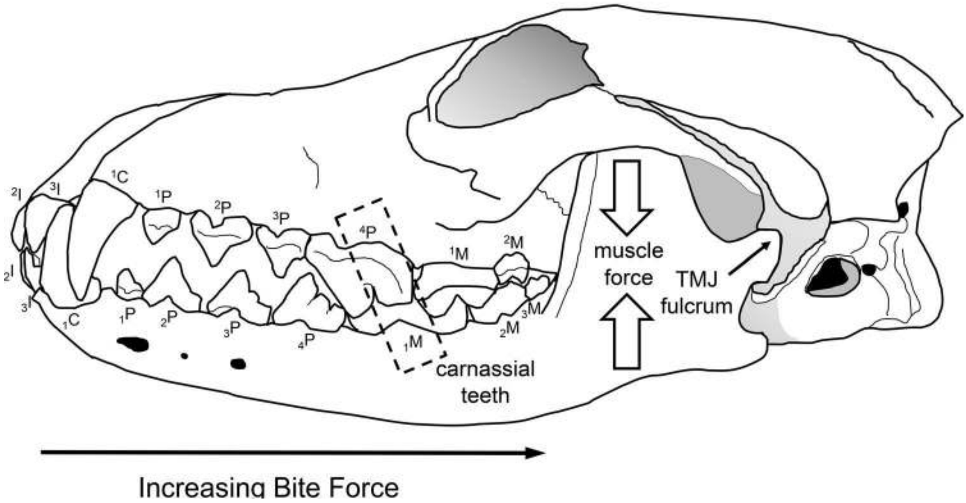

Figure 9.2 Mechanics of mandibular leverage, using a coyote (*Canis latrans*) skull, left side. The bite force increases closer to the fulcrum of the TMJ; force (primarily by the masseter and temporalis muscles) is supplied between the TMJ and the posterior-most teeth, and most shearing action occurs at the carnassials (^{4}P and $_{1}$M in the case of this species). Note that the least amount of bite force can be generated at the anterior teeth, which are employed to capture and dispatch prey, not crush bone.

molars) when the bone is too large to fit effectively into the mouth (Figure 9.3). The teeth adapted to do the principle amount of shearing (similar to two scissor blades meeting) in a carnivore are the *carnassial* teeth (Searfoss 1995). Large intact bones generally cannot be fit deeper into a carnivore's mouth than at the carnassial teeth or molars immediately posterior to them, which also is the site of the maximum amount of bite force that can be applied. Larger bones, which normally are stronger overall (e.g., long bone shafts or mandible bodies), therefore cannot be put into the mouth as deeply as smaller, weaker bones (e.g., ribs, partial vertebrae, or sternum), which conversely do not require as much crushing force. Larger and more durable bones, especially long bones, therefore are typically attacked incrementally by bone gnawers, which must wear down a bone by slow fragmentation. The fragments created are often consumed.

Maximum bite force (Table 9.1) varies greatly among taxa, although few have been measured to date. The difficulties in gathering data on the maximum bite force of wild species have been reported frequently (Binder and Van Valkenburgh 2000; Erickson et al. 1996, 2004; Lindner et al. 1995; Wroe et al. 2008). In comparison, among the greatest bite force for an extant predator species is that of the great white shark (*Carcharodon carcharias*), although this force is applied over multiple shearing teeth instead of concentrated on chisel-shaped teeth anchored in bony jaws, as is the case with spotted hyena (*Crocuta crocuta*). Lions (*Felis leo*) have been recorded as generating similar amounts of bite force, but this species lacks the specialized bone-crushing teeth of hyenas. Humans and various breeds of domesticated dog (*Canis familiaris*) have generated a wide range of bite force data, likely dependent upon the characteristics of the tested individuals including age and size (Edmonds and Glowacka 2020; Hidaka et al. 1999). Note that the ability of dogs, a species that is perhaps the most common gnawer on bones of forensic interest, to gnaw and crush bone varies greatly.

Figure 9.3 Domestic dogs (*Canis familiaris*) gnawing on pig (*Sus scrofa*) long bones for taphonomy experiments. Note the typical posture of positioning the bone with the front legs so that the bone can be attacked not with the anterior teeth but with the carnassials on the side, closer to the fulcrum of the jaw at the TMJ joint. Note also that the dogs ignored the exterior adhering soft tissue and proceeded directly to the fat contained inside the bones.

Long Bone Gnawing Sequences

This battle of attrition waged by the bone gnawer vs. a long bone means attacking by way of the epiphyses, where the cortical bone is much thinner than that along the diaphysis (Figure 9.4). The usual gnawing proceeds as gradual crushing followed by large amounts of consumption of these dislodged fragments (which contain bone grease). As gnawing proceeds, the marrow cavity is gradually exposed, although the contents cannot yet be removed. As the gnawing moves toward the diaphysis, the cortical bone continues to get thicker. As a result, more effort must be expended to detach each bone fragment. Each

Table 9.1 **Maximum Bite Force (lbs-force) Measured for Multiple Taxa**

Taxon	Maximum Bite Force (lbs-force)	Source
Great white shark (*Carcharodon carcharias*)	>4000	Wroe et al. (2008)
Alligator (*Alligator mississippiensis*)	2960	Erickson et al. (2004)
Spotted hyena (*Crocuta crocuta*)	1000	Binder and Van Valkenburgh (2000)
Lion (*Felis leo*)	940	Erickson et al. (1996)
Wolf (*Canis lupus*)	400	Erickson et al. (1996)
Dusky shark (*Carcharhinus obscurus*)	330	Erickson et al. (1996)
Domestic dog (*Canis familiaris*)	3–313	Lindner et al. (1995)
Human (adult)	55–280	Hidaka et al. (1999)
Human (juvenile to adult)	1–129	Edmonds and Glowacka (2020)
Domestic cat (*Felis catus*)	27	Christiansen and Wroe (2007)

Figure 9.4 Human proximal femur sawn lengthwise to show the range in cortical thickness at the extremities, from less than 1 mm at the epiphyses (left) to close to 1 cm along the diaphysis (right) in this individual. The scale is in cm.

freshly exposed break surface is subjected to more dental abrasion as the bone is gnawed, often forming a rounded edge on the newly exposed surface (Fisher 1995). Gnawing often continues until the marrow cavity is exposed sufficiently for a portion of its contents to be accessed and may continue until all of the marrow is consumed. Abandonment may occur sooner. The final result, if the long bone is attacked long enough from both ends, is the formation of a bone *cylinder* (a change from a tube with closed ends to a tube with open ends).

The less dense (Chapter 4) epiphyses of large mammal long bones are often attacked preferentially to the stronger (denser) ones on the same bones. An example of this general gnawing pattern comes from a cave den sample from Masai Mara National Reserve, Kenya (Kerbis Peterhans 1990; Pokines and Kerbis Peterhans 2007). In this case, gnawing data are presented on ungulate (hooved animals, including a range of sizes from cape buffalo [*Syncerus caffer*] to small antelopes such as Thomson's gazelle [*Gazella thomsoni*]) long bones. This size range includes humans. These bones were transported from kill sites to a den for further gnawing by spotted hyenas. The results of gnawing on long bones are presented in Table 9.2. A clear pattern emerges of a preferential gnawing on weaker portions of long bones, even by the terrestrial scavenger species most adapted to effective bone gnawing. Among the humeri (n = 110), which among all large terrestrial mammal species have a relatively weak proximal portion and strong, dense distal portion (Chapter 4), the proximal portion tended to be destroyed preferentially. Only one proximal humerus had not been destroyed by gnawing, although multiple complete humeri were present and had not yet undergone significant gnawing. In addition, 13 adult humeri in this sample were gnawed on both the proximal and distal ends such that only the shaft portion remained (i.e., a bone cylinder). Radii (n = 105) tended to have a weaker distal relative to proximal

Table 9.2 Long Bone Survivorship: Spotted Hyena (*Crocuta crocuta*) Gnawing on Combined Large Ungulate Sample, Masai Mara, Kenya

Humerus (n = 110)			Radius (n = 105)		
Portion	Total	%	Portion	Total	%
Complete	16	14.5	Complete	32	30.5
Cylinder	13	11.8	Cylinder	20	19.0
Diaphysis (unfused)	16	14.5	Diaphysis (unfused)	2	1.9
Distal	14	12.7	Distal	1	1.0
Distal half	27	24.5	Distal half	1	1.0
Distal + shaft	18	16.4	Distal + shaft	3	2.9
Proximal	1	0.9	Distal epiphysis	2	1.9
Shaft fragment	5	4.5	Proximal	13	12.4
			Proximal half	21	20.0
			Shaft fragment	10	9.5

Femur (n = 79)			Tibia (n = 102)		
Portion	Total	%	Portion	Total	%
Complete	10	12.7	Complete	16	15.7
Complete minus head	3	3.8	Cylinder	7	6.9
Cylinder	20	25.3	Diaphysis (unfused)	1	1.0
Diaphysis (unfused)	13	16.5	Distal	15	14.7
Distal	3	3.8	Distal half	21	20.6
Distal half	6	7.6	Distal + shaft	17	16.7
Distal + shaft	5	6.3	Distal epiphysis	8	7.8
Distal epiphysis	2	2.5	Proximal	4	3.9
Proximal	1	1.3	Proximal half	2	2.0
Proximal half	2	2.5	Proximal + shaft	1	1.0
Proximal epiphysis	2	2.5	Proximal epiphysis	2	2.0
Shaft fragment	12	15.2	Shaft fragment	8	7.8

Source: Pokines and Kerbis Peterhans (2007:1914).

portion. The distal portion was destroyed preferentially, although as with the humeri sometimes both ends were gnawed away, leaving a bone cylinder. The femora (n = 79), with relatively weak proximal and distal extremities, tended to be gnawed on both ends: few proximal or distal portions survived among bones that had undergone gnawing. The tibiae (n = 102) exhibited a pattern similar to the humeri. Their weaker proximal ends were destroyed preferentially to their stronger, denser distal ends, which survived preferentially.

This pattern is also followed in a more frequently encountered example than predatory hyena behavior. In an experiment, three large dogs (ranging from 26 to 45 kg) were fed mostly defleshed, commercially available large juvenile pig long bones in multiple settings. In one test series, a fresh pig humerus was given to each of the three dogs for timed feeding bouts of 6, 12, 18, and 24 min. All feeding was by individual dogs acting on individual elements. The three dogs were observed for the entire feeding periods, and no discarded fragments were noted. In the other series of tests, the same dogs were given pig humeri and femora and allowed to gnaw upon them for up to 24 h, at which point they were taken away if the dogs had not already abandoned them. Feeding in the latter series could have involved more than one dog in succession, as the dogs were not monitored during the

Figure 9.5 Juvenile pig humeri gnawed on by a large (26 kg) domestic dog (*Canis familiaris*). Left to right: 6 min of gnawing, 12, 18, and 24 min. The proximal end in each case has been gnawed preferentially to the distal end. Note that detached epiphyses have been glued to their original locations after cleaning. The scale is in cm.

entire span. All bones were then macerated for examination. Figure 9.5 shows one series of 6-, 12-, 18-, and 24-min feeding bouts from one of these dogs. The majority of damage proceeded in a linear progression, with increasing amounts of destruction of the proximal end of both the humeri and femora over time. A very similar damage sequence was produced by one of the other dogs, while the third (and oldest) dog showed variable amounts of interest. It is noteworthy that despite the edible meat attached to the bones, in each case, the dog was more attracted to gnawing the bone (likely to obtain the fat, large quantities of which were lacking from their usual diet) than consuming the attached tissue, which was largely ignored over short intervals.

When given more time, in each case, these dogs reduced the pig humeri and femora to a cylinder by destroying both ends and exposing the marrow, little or none of which was left upon retrieval. Figure 9.6 shows a typical sample of these bones. In the most extreme case (Figure 9.7), little of the shaft cylinder remained. This element, with a little more gnawing, could have been reduced to nothing but fragments and possibly consumed entirely.

Multiple studies comparing the results of a range of carnivores and large mammal prey (Becker and Reed 1993; Behrensmeyer 1991; Brain 1981; Carson et al. 2000; Domínguez-Rodrigo 1999; Faith and Behrensmeyer 2006; Haglund 1997a; Harding and Wolf 2006; Haynes 1980a,b; Hill 1980, 1989; Hill and Behrensmeyer 1984; Pobiner 2007; Pobiner et al. 2020; Pokines and Kerbis Peterhans 2007), including those which specifically address large carnivore consumption of humans or other large primates (Galdikas 1978; Haglund 1997a; Haglund et al. 1988, 1989; Hart and Sussman 2008; Horwitz and Smith 1988; Kerbis Peterhans et al. 1993; Kerbis Peterhans and Gnoske 2001; Merbs 1997; Milner and Smith 1989; Morton and Lord 2006; Pickering and Carlson 2004), indicate that once consumption has begun, the weaker, or less dense, elements have a much poorer chance of survival and are often consumed entirely. In general, stronger elements equate with long bone diaphyses and mandibular bodies, with the other elements of the human body more easily consumed/fragmented due to their less dense construction (especially the cranium,

Figure 9.6 Juvenile pig (*Sus scrofa*) long bones gnawed by large (26–45 kg) domestic dogs (*Canis familiaris*) until abandonment, less than 24 h later. Note that in each case, the elements (humeri and femora) were reduced to a cylinder. The scale is in cm.

Figure 9.7 Juvenile pig (*Sus scrofa*) humerus reduced to a residual cylinder by large domestic dog (*Canis familiaris*) gnawing, less than 24 h later. The scale is in cm.

Figure 9.8 Crenellated margin, along with additional fragments, caused by carnivore gnawing to a humerus, likely by canids. The scale is in cm.

sternum, vertebrae, ribs, scapulae, and innominates) and/or smaller size (hand and foot elements), making it possible to swallow them whole or after minor fragmentation.

Direct Marks on Bone

Crenellated (or *Crenulated) Margins* (Figures 9.8 through 9.10) are the jagged edges left behind after bone removal (Table 9.3). Once these margins have been exposed, that damaged location can display *edge polish*, which is formed by the repeated wear of gnawing teeth (or tongue) against the exposed margin of a bone (Figure 9.11). This tends to occur where thicker sections of cortical bone have been exposed by flake removal, as these areas of bone can withstand forces of wear without fracturing as quickly (i.e., edge wear formation requires an area of robust bone). Repeated gnawing on a weaker bone or portion

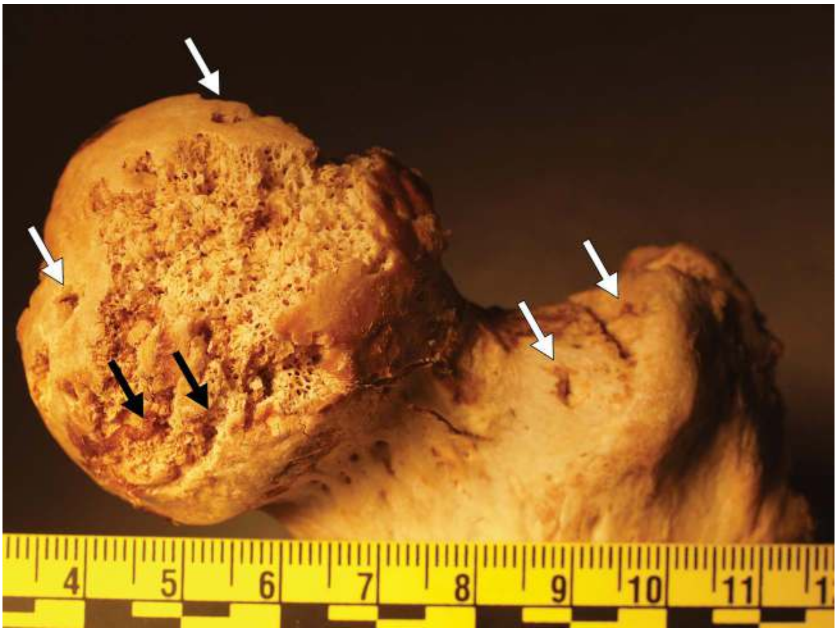

Figure 9.9 Proximal femur with crenellated margins, punctures (white arrows), and some furrows (black arrows). The scale is in cm.

Figure 9.10 Anterior mandible after domestic dog gnawing, showing pale underlying bone on each side where crenellated margins have been formed and multiple tooth pits (arrow) along the inferior portion. The scale is in cm.

thereof tends to remove a new flake and expose a clean break with an unpolished surface. Edge polish therefore is most often formed on long bone shafts as the gnawing proceeds toward midshaft from either end, and the cortical bone gets progressively thicker and more difficult to fragment. Weaker bones, such as vertebrae (Figure 9.12), often undergo crushing and can be fragmented into pieces and consumed, leaving few traces.

Other direct markers of carnivore gnawing damage are often divided among four main categories of *tooth marks* left behind on bone, which have been defined through general usage in the taphonomic and zooarchaeological literature (Binford 1981; Fisher 1995; Haynes 1980b, 1981, 1983; Lyman 1994:205–214; Pobiner 2007, 2008; Pokines and Kerbis Peterhans 2007; Udoni 2019; Udoni et al. 2021) as given below and in Table 9.3.

Tooth Pits (Figure 9.10) are circular to irregular-shaped depressions in the cortical bone, which do not penetrate to the bone interior (i.e., either cancellous bone or the marrow cavity, brain case, or other interior space). These are defined as having a maximum length no more than three times their maximum width.

Tooth Punctures (Figure 9.13) are deeper depressions that do penetrate into the interior, and also have a maximum length no more than three times their maximum width. Since full penetration of the cortical bone is involved, the margins of a tooth puncture tend to be more broken/crushed in form than tooth pits (Pobiner 2007:167). Tooth punctures may preserve the shape of the tooth that caused them, which potentially may be used to identify which species or species size class did the gnawing. Paired/multiple tooth punctures may also help in identification, as in the case of suspected leopard (*Panthera*

Table 9.3 Definitions of Tooth Marks and Other Carnivore Gnawing Damage

Term/Definition

Pit: A tooth mark that does not penetrate the cortical bone and is <3X long as it is wide.

Score/Striation: A tooth mark that does not penetrate the cortical bone and is >3X long as it is wide.

Puncture: A tooth mark that does penetrate the cortical bone and is <3X long as it is wide. Punctures may be formed as focused areas of deeper bone loss in already exposed cancellous bone.

Furrow: A tooth mark that does penetrate the cortical bone and is >3X long as it is wide. Furrows also may be formed as linear areas of deeper bone loss in already exposed cancellous bone.

Scooping: Removal of deep areas of cancellous bone from gnawing; broader than furrowing. Rodent wet bone gnawing also produces scooping, though generally smaller and more localized.

Gripping Mark: Striations and pits found along diaphyses/shaft, associated with a carnivore holding a bone in its mouth for transport or gnawing maneuver.

Crenellated (or Crenulated) Margin: Irregular margins of bone formed by gnawing; also termed ragged, jagged, etc.

Edge Polish: The rounding of already exposed fracture margins from continued gnawing to that new surface.

Scalloping: Regular wavy margins left by a combination of crenellation and edge polish; has been noted from captive ursid gnawing. (See Udoni et al. 2021 for examples.)

Peeling: Stripping away of thin layers of cortical bone, usually by a pulling action with the anterior teeth; has been noted among human-, suid-, and ursid-altered assemblages. (See "Pig Gnawing Characteristics" section, below, for an example.)

Kennel Pattern: Excessive gnawing from the boredom of captive or domestic animals where significant rounding of gnawed margins is formed; sometimes found among wild taxa persisting in gnawing the same bone.

Sources: Arilla et al. (2014); Binford (1981); Fisher (1995); Haynes (1980b, 1981, 1983); Lyman (1994:205–214); Pobiner (2007, 2008); Pokines and Kerbis Peterhans (2007); Roselle et al. (2019); Udoni (2019); Udoni et al. (2021).

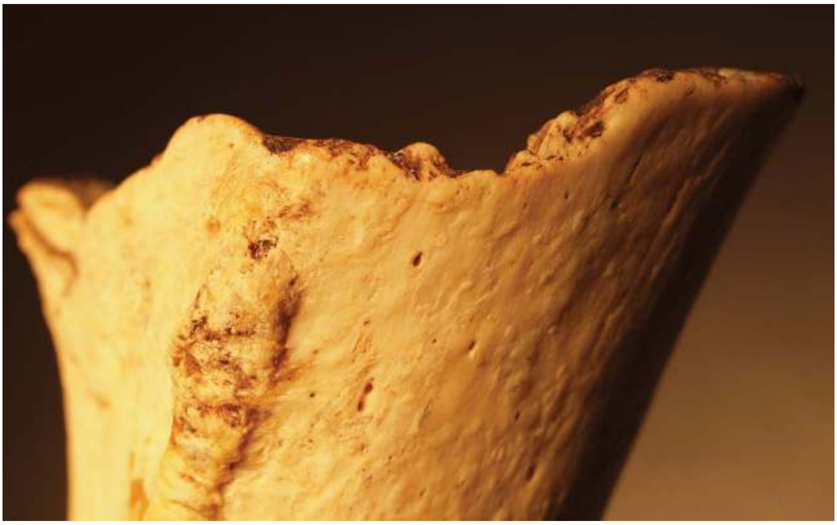

Figure 9.11 Long bone showing a crenellated margin from carnivore gnawing that has subsequently been rounded by more gnawing of the exposed margin, forming edge polish. The scale is in cm.

Figure 9.12 Cervical vertebra showing crushing to the body and other damage from carnivore gnawing. The scale is in cm.

Figure 9.13 Humerus head showing multiple punctures from carnivore gnawing. The scale is in cm.

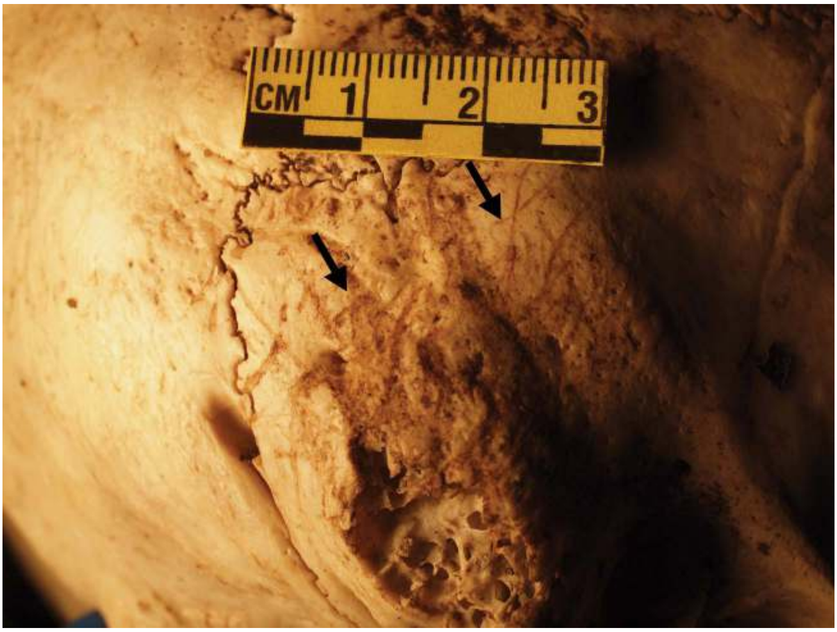

Figure 9.14 Right mastoid area showing multiple striations (arrows) from carnivore gnawing, superior to an area of missing bone. The scale is in cm.

pardus) carrying an *Australopithecus* cranium from the South African early hominin site of Swartkrans (Brain 1981). In this example, the distance between paired canine punctures is consistent with that typically found in leopards. The term tooth punctures more generally may be applied to holes made into accompanying artifacts, such as clothing associated with remains.

Tooth Scores (or *Striations*) (Figure 9.14) are the same penetrative form as tooth pits, only these are three times or more longer in maximum length than width. Scores may occur at most places on the bone, not preferentially on a gnawed extremity, as they often mark where the bone was gripped for transport or repositioning by a carnivore. Scores located randomly along a long bone diaphysis therefore are sometimes termed *gripping marks* and are usually formed by bone manipulation for gnawing or to secure it for transport. These marks may also be comprised wholly or partially of tooth pits, although due to their usual location along a diaphysis, they rarely include a puncture or furrow component. Tooth scores are also sometimes formed in a parallel manner by multiple teeth dragging simultaneously.

Tooth Furrows (Figure 9.9) are in the same penetrative form as tooth punctures, only these are three times or more longer in maximum length than width. Tooth furrows can also be formed in cancellous bone that was exposed by previous gnawing, forming a deeper groove in a broader area of bone loss. Furrows are often destroyed by continued gnawing, as all of the cancellous bone of a long bone epiphysis and metaphysis restricts access to the marrow cavity and often gets removed by additional gnawing.

Pits and punctures tend to be formed by direct pressure of the tooth approximately perpendicular to the bone surface, while scores and furrows tend to be formed by the dragging of the tooth across the surface (Pobiner 2007:167–168). The latter may be V- or U-shaped in cross section, varying by the shape and angle of the tooth. Gnawing damage

Table 9.4 Characteristics of Gastric Corrosion on Bone

- Derived from carnivore/omnivore feces, regurgitation, or stomach contents
- Affects fragments or small whole elements
- Thinning/feathering of edges
- Windowing of bone common
- Sculpted appearance to cortical surfaces
- Hair/fur often imbedded in hollow spaces
- May be accompanied by indigestible remains (hair, fur, feathers, clothing, etc.)

also may be so extensive in one area that individual marks can no longer be differentiated, or that portion of bone has already been completely removed. Such areas are simply grouped under the general term *gnawing damage*, although individual tooth marks frequently are preserved at or past the margins of this damaged or missing area.

Gastric Corrosion

The bone fragments produced by gnawing (and intact, small elements such as carpals and phalanges) are often consumed by the carnivore, either for digestion or later regurgitation along with less digestible body portions (hair, hooves, etc.). *Gastric corrosion* often appears on these flakes of bone (or small bones consumed whole, such as carpals) and is characterized by a sculpted appearance (Table 9.4; Figures 9.15 and 9.16) on cortical surfaces, thinning or sharpening (*feathering*) of exposed margins as their thickness is eaten away (Esteban-Nadal et al. 2010; Payne and Munson 1985; Schmitt and Juell 1994), and *gastric windowing* (Figure 9.16), where the digestive acid has eaten small holes through the bone or expanded existing foramina. These flakes, found in regurgitation piles or feces, often have their pore spaces packed with hair or fur. *Corrosion* as used here refers specifically to acidic damage to bone. The term *erosion* is applied to more general loss of bone, the sources of which may include acidic damage, plant action, abrasion, and excavation damage.

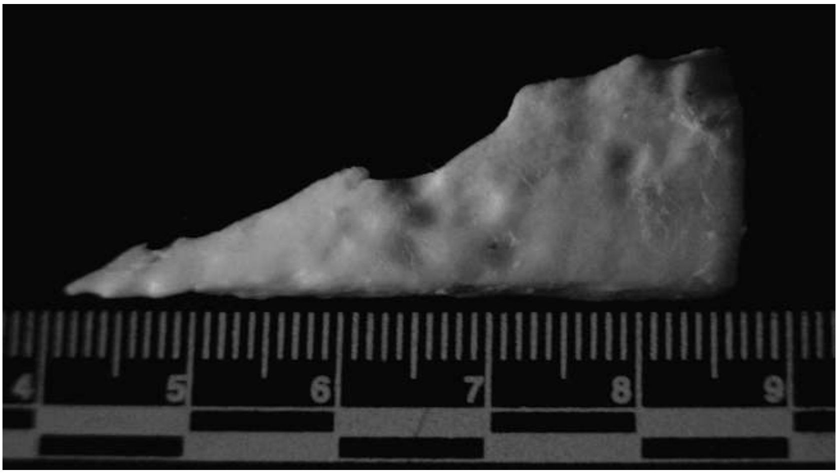

Figure 9.15 Gastrically corroded (previously machine-butchered; note right-angle cut on bottom and right sides) nonhuman long bone fragment, derived from domestic dog (*Canis familiaris*) vomit. Note the sculpted appearance of the surface. The scale is in cm.

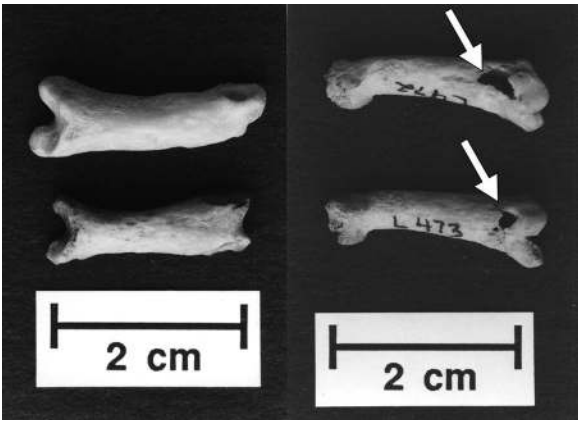

Figure 9.16 Gastrically corroded nonhuman phalanges, retrieved from striped hyena (*Hyaena hyaena*) feces, Israel. Note the sculpted appearance to the surfaces and windowing (arrows). (From Kerbis Peterhans 1990; used with permission.)

Gastric corrosion may mimic the effects of acidic soil corrosion (Chapter 5), since the chemical processes are largely the same. Gastric corrosion, by definition, can attack only fragments or whole bones small enough to be consumed by a carnivore (Esteban-Nadal et al. 2010; Payne and Munson 1985; Schmitt and Juell 1994). While acidic soil certainly will cause damage to small pieces of bone as well, it also very visibly attacks bones far too large to have been swallowed (Chapter 5). The more fragile elements, particularly the epiphyses, are damaged preferentially, and large reductions in the diameter of long bones can be caused by the gradual eating away by acidic attack. Differing frequencies in skeletal part recovery are also a key discriminating factor, since gastric corrosion must be accompanied by a large amount of bone gnawing and breakage. Payne and Munson (1985) noted that domestic dog digestion of bone fragments recovered from their feces removed all clear traces of previous gnawing on those fragments; Schmitt and Juell (1994) noted similar findings for bone fragments recovered from coyote feces. Fragments with gastric corrosion, since they are dietary in origin, also likely contain a mixture of species including smaller vertebrate taxa whose bones are more likely to be swallowed whole and therefore survive the digestive process in an identifiable state (Schmitt and Juell 1994; Stiner 1994).

Body Part Consumption Sequences

With a notable exception (see below in this section), the carcasses of most large mammals deposited into terrestrial environments tend to be consumed in a patterned body portion sequence (Table 9.5), and this pattern is followed by a variety of large mammal predators or scavengers throughout the world (Blumenschine 1986, 1988; Domínguez-Rodrigo 1999; Haynes 1980b; Kruuk 1972; Pobiner 2007; Pobiner et al. 2020). The degree of similarity in this regard is striking and therefore likely a product of accessible nutrients relative to expended effort (Blumenschine 1986), although the effects of ease of detachment of some portions of a body for transport elsewhere must be considered. In general, the highest yield/least effort portions of the body are consumed first, followed in the order of decreasing yield/greater effort. Other variables that affect consumption are intraspecies competition

Table 9.5 Carnivore Consumption Sequences

	Haynes (1980b)	Haglund (1997a)	Blumenschine (1986)
Consuming taxa	Large canids	Large canids	Spotted hyena, lion, and vultures
	(*Canis lupus*)	(*C. latrans* and *C. familiaris*)	(*Crocuta crocuta*, *Panthera leo*, and mult. species)
Consumed taxa	White-tailed deer (*Odocoileus virginianus*)	Humans	Large game, size classes I–V (small antelopes to elephants)
MNI of consumed taxa	n = 94	n = 53	n = 260
Source	Kill/scavenged sites	Scavenged sites	Kill/scavenged sites
Location	Minnesota, USA	Pacific NW, USA	Tanzania
Environment	Boreal forest	Boreal forest	Savanna
Consumption Sequence: **Start**	• Paunch penetrated; organs and blood	• Throat/face	• [Internal organs]*
	• Upper hindquarters	• Thoracic elements/ internal organs	• Hindquarters flesh
	• Ribs and vertebrae	• Legs consumed/ detached	• Forequarters flesh and thoracic cage
	• Upper fore legs, shoulder	• Disarticulation of remaining portions	• Head flesh
	• Throat/face	• Disarticulation/ gnawing of elements	• Hindlimb marrow
	• Disarticulation of limbs		• Forelimb marrow
Finish			• Head contents

* Internal organs were not a specific part of this study, which concerned the skeletal effects of scavenging.

(number of individuals feeding), the need to provision juveniles awaiting feeding at a den, interspecies competition, the size of the carcass being eaten, the developmental age of the deceased, the accessibility of body parts, and the relative availability of food resources in that environment. Consumption sequence patterning affects both the skeletal elements most likely to be consumed and the order in which they become detached from a skeleton and made available for transportation away from the scene of initial deposition.

The abdominal area normally gets fed upon first in order to gain access to the internal organs. This venue of attack requires the least amount of effort relative to the nutritional gain, as little bone is in the way besides the relatively thin and weak ribs and sternum, and these can be largely bypassed at this stage. Viscera are sometimes already partially consumed before death has even occurred, as some carnivores such as spotted hyenas (*Crocuta crocuta*) kill their prey by evisceration (Kruuk 1972). In the case of smaller carnivores or other small scavengers being the first ones to happen upon a fresh carcass, this area allows access to the heart, liver, lungs, and other soft organs without the need for bone to be destroyed. Early feeding therefore largely leaves bone undamaged and undispersed.

Feeding (Blumenschine 1986) normally proceeds to the upper hindquarters/rump area, as this is the largest mass of muscle tissue available, and the associated skeletal elements are contained well within. Feeding on this area can often cause disarticulation of one or both hind legs. Feeding then proceeds to the upper forequarters as the next largest muscle mass available. Little bone is damaged in this stage, as the pursued nutrients are largely external, but disarticulation of the forelimbs begins. Disarticulation of the forelimb from the thorax is expedited by the lack of interlocking skeletal articulation, including the absence of a clavicle in ungulate species. Feeding into the thoracic cage causes large amounts of damage to the ribs, vertebrae, and sternebrae, as these easily destroyed elements are often consumed with their associated soft tissue or at least snapped off through direct gnawing action or through the mass of the consuming species pressing down upon them. The external soft tissue of the head and throat area (including the tongue) is pursued next. While little protected, it represents a lower-yield portion of the carcass. This feeding naturally may cause disarticulation of the skull from the rest of the carcass and the mandible from the cranium. With the majority of easily accessible external soft tissue consumed at this point, attention normally turns to the skeletal elements themselves and the nutrients that they contain in the form of stored fat within the marrow cavity and cancellous spaces. Hindlimb long bones (femur and tibia) normally are attacked first, followed by the forelimb long bones (humerus and radius/ulna). The rear limb long bones contain on average larger marrow yields compared with the forelimb long bones of the same species (Brink 1997; Lupo 1998; Madrigal and Holt 2002; Morin 2007), hence their higher nutrient value to consuming species (Chapter 4). Head contents tend to be pursued last. While the braincase contents include a high proportion of valuable fatty tissue (Stiner 1994), these tend to be well protected in adult animals, including humans. The cranial size and shape, with its gradual curve, are harder for a carnivore to grip and gnaw through. It is also in many cases too large to transport, depending upon the relative size of the consumed to the consuming species (Pokines and Kerbis Peterhans 2007). Other skeletal elements generally are more transportable, in partial articulation or not, and dispersal begins as soon as each body area begins to be consumed. The later stages of consumption (marrow extraction) therefore often take place away from the initial kill/deposition site, where more time can be expended upon this harder to extract but valuable caloric source.

Variations in this sequence do occur, as noted by Haynes (1980b) in his study of wolves (*Canis lupus*) consuming white-tailed deer (*Odocoileus virginianus*) in Minnesota, USA (Table 9.5). His research noted that upper hindquarters tend to be consumed prior to thoracic portions, *contra* the research of Blumenschine (1986) on the Tanzanian savanna. Since Haynes (1980b) reported a single carnivore and prey relationship, it is possible that the relative size of the consuming species and particular nutrient yield pattern of the prey increase the desirability of the thoracic region in this case, or that more fragmentation of the thoracic region occurs during accessing or consumption of the internal organs. Haynes (1982) studied wolf winter consumption sequences on two larger species, moose (*Alces alces*) and bison (*Bison bison*), in Canada and the USA and found that their carcasses were consumed in much the same pattern (1982:271): internal organs/rump, including early rib damage; shoulder area; pelvic area; vertebral damage; greater damage to upper long bones and scapulae; soft portions of the head; followed by greater consumption/damage to bones throughout the body.

Haglund et al. (1989) and Haglund (1997a) (Table 9.5) reported a more forensically important variation regarding human consumption and dispersal sequences by large canids (*Canis latrans* and *C. familiaris*) in the US Pacific Northwest. They found that consumption normally began with the throat and facial area of humans, then proceeded in almost the same pattern typical of other large mammals: abdominal/internal organs and thoracic region, legs, then the remaining portions. This pattern variation may be explicable by human bodies usually being covered by clothing, which tends to be of the heavier variety in their study area in most seasons. The facial and throat area of a human body therefore might present on average the easiest point at which to begin consumption by a large canid, with consumption generally following from there to the areas of the body with a higher nutrient payoff relative to effort expended. Clothing also likely hinders dismemberment and may alter the transportability of disarticulated human skeletal elements. This apparent difference in consumption pattern between humans and other large mammals theoretically would be more pronounced in winter, where human bodies typically would average greater and thicker clothing coverage in a variety of scenarios involving outdoor deposition.

Bone Dispersal

Types of Dispersal

Large and small carnivores also disperse bone away from the point of initial body deposition (Haynes 1982, 1983; Hill 1979; Moraitis and Spiliopoulou 2010). In forensic terms, whether a bone was entirely consumed or transported so far away from an initial crime scene that it could not be located, the material result is the same: the bone is not available for analysis and can shed light only on the disarticulation/dispersal status of the remains. *Primary dispersal* is defined here as bone movement away from their point of initial deposition, without any prior movement of the entire, intact mass of remains as a unit. Dispersal in any environment can range from zero (remains still intact on the surface or buried) through severe, with few if any traces of the remains at their place of initial deposition. Some dispersal is likely under most circumstances from incidental agencies of bone dispersal, such as downslope wash, feeding displacement, and accidental trampling by wildlife. Even buried remains may undergo minor dispersal if partially dug into by scavengers or through the efforts of fossorial (burrowing) fauna displacing bone after the soft tissue has decomposed.

More advanced dispersal is likely the result of dispersal agents including mammalian scavengers, porcupines (Kerbis Peterhans 1990), and flowing water channels (Chapter 6). Larger teams employing integrated searching techniques are necessary to recover remains in these situations (Chapter 17), especially where more time has passed and vegetation (living and dead) has built up over and obscured isolated elements/fragments. As dispersal increases, more intensive survey techniques will be required, including grid searches with members advancing at ground level and the use of cadaver dogs. Heavier dispersal likely corresponds with a greater postmortem interval (PMI) and/or amounts of large carnivore involvement, and the recovered remains are likely in a poorer preservational state. Heavy amounts of dispersal also likely involve more species, including the common scenario of scavenging and dispersal by large mammals, followed months or years later by movement of these surviving elements by large rodents gnawing on the now-dry bones. The taphonomic alterations left upon the bones likely increases as the PMI and amount of dispersal both increase. Some species such as hyenas habitually transport individual pieces of remains for feeding elsewhere such as a home den, normally causing severe dispersal of remains (Pokines and Kerbis Peterhans 2007). Severe dispersal also can occur where mass flooding events spread remains downstream.

Secondary dispersal is defined here as occurring when remains have been moved, largely intact, from the point where initial deposition/death occurred to another location.

From this secondary deposition point, secondary dispersal will then proceed. The movement of largely intact remains may be caused by (accidental or deliberate) deposition into water (Chapters 6 and 7), transportation of murder victims (Chapter 10), or caching or other transport behavior by large predators (see "Caching" section, below).

Causes of Dispersal

Dispersal begins as a direct result of feeding behavior: as a body is consumed, bones get disarticulated, then moved at least a short distance as limbs are detached from the axial skeleton, ribs are broken and removed, and the cranium is removed over the course of hours or days. It is also the typical behavior across a range of carnivores, large and small and including domesticated dogs (Hudson 1993; Kent 1981), wolves (Mech 1970; Willey and Snyder 1989), and bears (Carson et al. 2000), to remove portions of a carcass to feed on them in different location. Haynes (1980b) noted that single wolves typically removed carcass portions for gnawing away from the point of deposition yet usually within 30 m of it. This reduces interspecies and intraspecies competition for food by taking a small portion some distance from the main source. Feeding often continues within the sight of the main source, with repeated forays to secure more food, which is then removed to a safe distance (Arilla et al. 2019). Bones can in this manner be scattered tens or hundreds of meters from their site of initial deposition. Bones with or without meat attached are also deliberately transported by many species in order to feed their young at a denning site and also to feed nursing females and can lead to reconcentration of remains in other locations (see "Bone Reconcentration/Aggregation" section, below). Carnivore defecation also may occur repeatedly in the same locations in order to mark home territories (Kruuk 1972; Pickering 2001; Schmitt and Juell 1994). These many processes make dispersal as much a characteristic of carnivore interaction with bone as gnawing damage and means that bones may be transported several kilometers, making their recovery less likely.

The size of body portions ranging from partial, single skeletal elements up to major portions of a carcass that may be transported varies with the size of the consuming animal transporting that food item. Haynes (1982) observed wolves running through several hundred meters of deep (60 cm) snow carrying disarticulated lower limbs of bison (*Bison bison*). Research in Kenya indicates that transport of larger species' intact crania by spotted hyena (*Crocuta crocuta*) is usually restricted to the smaller ungulates in their diet or to the juveniles of such large species as Cape buffalo (*Syncerus caffer*) (Pokines and Kerbis Peterhans 2007). Transport of body portions this large by typical scavengers indicates that long-distance transport of partially articulated human remains is possible for many species.

Distance of Dispersal

The distance of dispersal can be far beyond the capacity of normal forensic recovery methods to process. In an extreme example, Horwitz and Smith (1988) detected movement of human remains, including crania, by striped hyenas (*Hyena hyena*) in Israel to a den site up to 25 km from their likely source, a hospital graveyard. In North America, dispersal distances are not known to be as large, but a part of this perception may be due to greater information loss and the lack of data regarding the most distant remains. Hyenas are known to transport and accumulate large amounts of bone in their dens (see "Bone

Reconcentration/Aggregation" section, below). Tracing bones to their probable source, whether by prey species behavior or known deposition location (such as with human cemeteries or food waste dumps), is more possible. Dry/open environments also may favor dispersal tracking when compared to wet/closed areas, as it is easier to locate bones on the ground surface with fewer visual impediments (Chapter 17). Humid/closed environments, including much of North America, make it harder to locate bones amid dense plant cover. The distance of maximum dispersal therefore may be greater than expected in these areas, as the most distant bones are also the most difficult to find.

The distance and degree of dispersal (Table 9.6) of human remains in an outdoor scene is of direct relevance to the expanded size of a scene, search methods necessary to process it, and the amount of bone recovery maximally possible (Chapter 17). Haglund (1991) found that coyotes (*Canis latrans*) and domestic dogs (*C. familiaris*) dispersed human remains frequently over 30 m from the point of deposition for surface remains in the Pacific Northwest of the USA. Some dispersal was found to extend over 350 m. Multiple experimenters have used pig (*Sus scrofa*) remains to model the dispersal of human remains. King et al. (2016) found dispersal up to 0.5 km. Other researchers (Beck et al. 2015; Keyes et al. 2020; Kjorlien 2004; Kjorlien et al. 2009; Morton and Lord 2006) found dispersal of tens of meters to be common, or as little as 15 m (Sorg et al. 2012). Spies et al. (2018) found that even a small carnivore species like Cape gray mongoose (*Galerella pulverulenta*) dispersed experimental pig bones up to 12.7 m. Young et al. (2015a) found experimentally that small-medium carnivores like red fox (*Vulpes vulpes*) and badger (*Meles meles*) could disperse various species of deer bones over 100 m. Arilla et al. (2019, 2020) found that small-medium carnivores, including red fox, were avid bone dispersal agents that caused much loss of experimental bone and dispersal of recovered bones for tens of meters. King et al. (2016) found that Virginia opossum (*Didelphis virginiana*) dispersed experimental pig remains less than 10 m.

Rodents also have been found to disperse bone. Old World porcupines (*Hystrix* spp.) have been noted to move bone as large as rhinoceros (*Diceros bicornis*) tibiae in Kenya (Pokines and Kerbis Peterhans 2007), although the distance is unknown but likely substantial, given the surrounding rocky terrain. These bones were concentrated into a den for gnawing (Alexander 1956; Dixon 1984; O'Regan et al. 2011) and generally had undergone significant subaerial weathering (Chapter 11) prior to collection. Smaller rodents, including eastern gray squirrels (*Sciurus carolinensis*) also frequently gnaw dry bone (see below), and some dispersal during this activity does occur. The present author (unpublished data) found dispersal by this squirrel species of dry white-tailed deer (*Odocoileus virginianus*) bones over 10 m, although most individual instances of bone displacement were only a few centimeters at a time during gnawing or foraging through leaf litter. Hockett (1989) found through examination of nests that a wood rat subspecies *Neotoma cinerea orolestes* could move bones of mule deer (*Odocoileus hemionus*), cottontail rabbit (*Sylvilagus nuttali*), and elk (*Cervus canadensis* [= *C. elaphus*]) up nearly vertical slopes up to 3.5 m. Hoffman and Hays (1987) found experimentally that the wood rat species *Neotoma floridana* readily dispersed dry bones left outside of their nests. The dispersed species included white-tailed deer (*Odocoileus virginianus*), domestic dog, raccoon (*Procyon lotor*), and smaller vertebrates. Approximately 46% of the bones had been moved at least 1 m by the end of the experiment, with the most distant movement being 5 m (for a dog pelvis). Vertical movement of 1–2 m also was common. Arilla et al. (2020) also recorded a wood mouse (*Apodemus sylvaticus*) moving a fresh, juvenile sheep vertebra.

Table 9.6 **Some Reported Maximum Bone Dispersal Distances by Scavenging Mammalian Taxa**

Dispersing Taxa	Dispersed Taxa	Maximum Dispersal Distances/Context	Source(s)
Hyaena hyaena	*Homo sapiens*	Up to 25 km; disturbed modern burials in Israel.	Horwitz and Smith (1988)
Canis latrans, C. familiaris	*Homo sapiens*	From 4 to 1200 feet (~1 to 365 m) for n = 38 scavenged cases in Washington, USA; maximum distances over 100 feet (~30 m) were common.	Haglund (1991)
Multiple small scavengers, including some vultures	*Homo sapiens*	43.6 feet (13.3 m) for a skull, much dispersal of other elements; experimental deposition in Texas, USA.	Moss (2012)
Ursus americanus	*Sus scrofa*	Partially intact pig carcasses (starting mass ≤ 45 Kg) moved up to 130.9 m, followed by secondary dispersal; experimental deposition in northern California, USA.	Bright (2011)
Canis latrans	*Sus scrofa*	<0.5 km; experimental juvenile pigs.	King et al. (2016)
Canis latrans, multiple other species	*Sus scrofa*	85 m for experimental juvenile pigs in Edmonton, AB, Canada; some dispersal followed game trails. Some entire carcasses dragged over 5 m.	Kjorlien (2004); Kjorlien et al. (2009)
Canis latrans, C. familiaris; also vultures	*Sus scrofa*	>25 m for experimental juvenile pigs in the Sonoran Desert, AZ, USA.	Beck et al. (2015)
Galerella pulverulenta	*Sus scrofa*	12.7 m for experimental juvenile pigs in South Africa.	Spies et al. (2018)
Vulpes vulpes, multiple other species	*Sus scrofa*	Up to 18.3 m (60 feet) for experimental juvenile pigs in Virginia, USA, some surface and some shallowly buried. One entire buried carcass removed out of study area by *V. vulpes*.	Morton and Lord (2006)
Canis latrans, multiple other species	*Sus scrofa*	93 m for experimental juvenile pigs in Massachusetts, USA.	Ricketts (2013)
Canis mesomelas, multiple other species	*Sus scrofa*	73.7 m for experimental juvenile pigs in unfenced area in Pretoria, South Africa; up to 42.8 m for fenced area, with directionality noted toward entry hole in fence but no dispersal beyond it.	Keyes et al. (2020)
Canis lupus	*Odocoileus virginianus*	Notes that up to 30 m of dispersal is common from kill sites for additional feeding; Minnesota, USA.	Haynes (1980b, 1981)
Vulpes vulpes, Meles meles	*Cervus nippon; Capreolus capreolus*	103.5 m, with the majority within 45 m; Dorset, UK.	Young et al. (2015a)
Vulpes vulpes; multiple other species	*Ovis aries* adult and juvenile; *Bos taurus* juvenile	Body parts, some cooked, from simulated archaeological hearths in the Spanish Pyrenees. 82.3% of 466 elements disappeared; maximum dispersal was 41 m.	Arilla et al. (2020)

(Continued)

Table 9.6 ***(Continued)*** **Some Reported Maximum Bone Dispersal Distances by Scavenging Mammalian Taxa**

Dispersing Taxa	Dispersed Taxa	Maximum Dispersal Distances/Context	Source(s)
Vulpes vulpes	*Capra hircus; Capreolus capreolus; Sus scrofa; Ovis aries*	Carcasses placed in Spanish Pyrenees; 47.3% of 3332 skeletal elements not recovered; 34.0% (n = 598) of recovered elements within 10 m radius; 29.1% (n = 513) 10–20 m; 23.0% (n = 419) 20–30 m; remaining 12.9% (n = 226) 30–55 m. Mean distance of retrieved skeletal remains was 16.9 m.	Arilla et al. (2019)
Sciurus carolinensis, multiple other species	*Odocoileus virginianus*	12.5 m for experimental dry deer bones in an urban park in Massachusetts, USA.	Pokines (unpublished data)
Neotoma cinerea orolestes	*Odocoileus hemionus*; *Sylvilagus nuttali; Cervus canadensis* [= *C. elaphus*]	Wood rat nests examined for bone content; dispersal distance included a minimum of 3.5 m up a nearly vertical slope.	Hockett (1989)
Neotoma floridana	*Odocoileus virginianus*; *Canis familiaris*); *Procyon lotor*; and smaller vertebrates	Experimental dry bones left outside of active wood rat nests; ~46% of the bones had been moved at least 1 m, with greatest distance of 5 m (dog pelvis). Vertical movement of 1–2 m common.	Hoffman and Hays (1987)
Didelphis virginiana	*Sus scrofa*	<10 m; experimental juvenile pigs.	King et al. (2016)

Bone Reconcentration/Aggregation

Bone Collectors

Multiple species also aggregate (usually heavily commingled) bone in locations away from their point of initial deposition, typically at a *denning* or other home site. The primary reasons are to continue feeding in a more protected location within one's home range, where it is less easy for interspecies competitors to steal food. The home den also often offers other amenities, such as shade, shelter, a location near a water source, and presumed continued access to other food sources. The provisioning of young, as discussed earlier, also occurs among many species, where carcass portions are brought to juveniles too young to participate directly in hunting activities or to nursing females. In North America, this primarily includes wolves, which hunt/scavenge within a home territory, and the pups are left in a home den during the spring and early summer (Fuller 1989; Kuyt 1972; Mech 1970; Peterson 1977). Food, between the time when pups are weaned but before they are old enough to hunt with the pack, is transported to the den, where the adults also may feed on it. Food also may be delivered to pups in the form of regurgitation (Harrison and Gilbert 1985; Mech 1970), which may contain bone fragments or whole small elements.

In the Old World, all three extant hyena species are avid bone collectors (Hill 1989; Horwitz and Smith 1988; Kerbis Peterhans 1990; Kerbis Peterhans and Horwitz 1992; Pokines and Kerbis Peterhans 2007), the fossil bone concentrations of which must be distinguished from accumulations by hominins (Behrensmeyer 1991; Blumenschine 1988; Brain 1980, 1981; Crader 1983; Domínguez-Rodrigo 1999; Tappen 1995). As indicated earlier, feeding in a favored tree or cave by leopards may concentrate bones, and these concentrations may have paleoecological implications (Brain 1981; Cavallo and Blumenschine 1989; Kerbis Peterhans 1990).

Den Characteristics

Most bone aggregation occurs at denning sites, which are important archaeologically, paleontologically, and forensically, as these depositional settings greatly increase the chances for the long-term preservation of osseous assemblages. Large animal dens throughout most world regions rarely have just one occupying species, as they tend to get reused by multiple species (Barthelmess 2006; Behrensmeyer 1991; Brain 1980; Harrison and Gilbert 1985; Kerbis Peterhans 1990; Pokines and Kerbis Peterhans 2007). This is true of more temporary dens, such as burrows or borrowed human structures (culverts, under buildings, etc.), or more permanent features (caves; see Figure 9.17). The former category tends to persist for decades, while the latter persists for millennia or longer—long enough temporal spans to accumulate large, commingled bone assemblages drawn from the surrounding area via multiple sources. The mixture of species that may occupy a single den in succession in large portions of North America include porcupines, canids (domestic dogs, wolves, and coyotes), lynxes (*Felis canadensis*), bobcats (*Felis rufus*), mountain lions (*Puma concolor*), and bears. These dens are used for adult and juvenile shelter and therefore also tend to build up large concentrations of feces, urine, hair, and arthropods that are attracted to these environments. Dens also may be used for hibernation (especially among bears), and deaths that occur during this period (weaker or unhealthy individuals) may build up large amounts of skeletal remains from these species. Dens also provide a protective environment for bone,

Figure 9.17 Example of dense animal bone reconcentration in a den, in this case by striped hyenas (*Hyaena hyaena*) and porcupines (*Hystrix* sp.) alternately using a cave in Hell's Gate National Park, Kenya.

which tends to preserve them for much longer than had they been exposed on the surface and subjected to subaerial weathering (Chapter 11).

Wolf dens in North America are not known to build up large amounts of osseous remains, as most wolf dens are earthen burrows, which are used only for a portion of a birthing season then abandoned (Fuller 1989; Kuyt 1972; Mech 1970; Peterson 1977; Thiel et al. 1998; and G. Haynes, pers. comm.). Some reuse of dens over multiple seasons does occur, and these locations have the greater potential to accumulate osseous remains in and around them from feces, regurgitation, and the remnants of feeding. As such, these locations are of forensic interest. Habitation of these sites by wolves is normally during the spring. Coyote denning, while less studied than that of wolves, is lesser in its potential to accumulate osseous remains (Harrison and Gilbert 1985) due to the higher proportion of vegetable foods and human garbage in coyote diet (Gehrt et al. 2009; Schmitt and Juell 1994).

Other species reconcentrate bone for other reasons. Multiple species of porcupines found throughout the world are avid bone collectors, transporting usually dry, weathered bone back to a home den for continued gnawing (Alexander 1956; Barthelmess 2006; Becker and Reed 1993; Kerbis Peterhans 1990; O'Regan et al. 2011; Pokines and Kerbis Peterhans 2007; Woods 1973). As noted above, wood rats also transport bones, along with many other assorted items, back to their nests and may incidentally pick up bones of interest to homicide investigators (Betancourt et al. 1990).

Caching

Multiple species *cache* prey for later, more paced consumption by moving usually an entire body/carcass and hiding it by shallow burial under loose sediments and plant debris or storing in a less accessible place, including trees, rock features, or underwater. Subsequent competition is reduced or excluded, and multiple bouts of feeding may occur on the same carcass for days. This behavior extends the time of access by the predator to the prey carcass, as no single large terrestrial predator can consume an entire large mammal approaching its own body mass in one feeding bout. Decomposition is also slowed through the partial exclusion of colonizing arthropods (Bischoff-Mattson and Mattson 2009).

Brown bears (*Ursus arctos*) (Bright 2011; Elgmork 1982; McLoughlin et al. 2002) and mountain lions (Murad 1997; Pierce et al. 1998) in North America are the most forensically relevant caching taxa, as are leopards (*Panthera pardus*) in Africa and southern Asia. Other taxa of bear are not known to cache prey as frequently (Elgmork 1982:607). Arilla et al. (2014), however, did not note caching behavior to occur among the brown bear kill and scavenge sites that they studied in the Spanish Pyrenees, so this behavior does vary and may be more common at kill sites. Leopards typically store kills in trees, usually for more immediate consumption and to prevent food from being stolen by larger/social predators (Brain 1981; Cavallo and Blumenschine 1989; Kerbis Peterhans 1990; Pobiner 2007). Caching behavior in this case may cause osseous aggregation, since leopards often return repeatedly to favorite feeding trees. Leopards also are known to store prey in caves (Simons 1966). Caching by bears and mountain lions is unlikely to cause osseous aggregation, as they only rarely return prey repeatedly to the same caching location (Elgmork 1982). Their storage of prey does cause immediate dispersal from its initial point of deposition (the kill site) and does serve to limit later dispersal by competing scavengers.

Caching behavior is likely more prevalent among these solitary predators such as brown bears and leopards, because pack predators, such as African wild dogs (*Lycaon pictus*), can consume single prey items much more rapidly. Some exceptions have been noted among pack predators, such as spotted hyenas caching prey (Kruuk 1972), although these exceptions tend to occur when these species are hunting alone. Food transport among pack carnivores, due to interspecies competition, is more likely to take the form of moving portions of a carcass for feeding elsewhere. Some of these portions can be hidden, as among canids. This includes stereotypical bone-burying behavior of domestic dogs, as well as similar behavior among their wild relatives, including African wild dog (Malcolm 1980).

Distances of carcass transport for caching purposes vary by individual, predator species, size of prey, and environmental conditions. Prevalence of cover is also a likely factor, as ground-dwelling predators living in more open environments (e.g., savanna) have less opportunity to hide carcasses effectively. Mountain lions, bears, and leopards typically cache whole carcasses after predation. The latter species is more observable in this behavior than the others, since it usually terminates with the carcass dragged up a tree for feeding, and the need for cover to prevent its loss to scavengers is greatly reduced. Little direct observational data exist on this behavior, as both a singular kill episode and cached carcass must be linked. The location of initial predation/carcass deposition may contain only small traces of the predation incident, including blood, hair, environmental disturbance (foliage displacement, tracks, etc.), and, in the case of human prey, also artifactual evidence. Leopards can drag small antelopes approaching their own body mass up a feeding tree (Brain 1981). It is unknown how much transport was required to reach the trees, but distances on the order of hundreds of meters are plausible, given the dispersal of game and suitable feeding trees in that semi-arid savanna environment.

Caching therefore can greatly increase the initial dispersal category of remains, given that they are normally removed some distance from their kill site. Secondary dispersal likely occurs from the point of caching/feeding, unless the remains are abandoned or lost for some reason.

Carnivore Gnawing Characteristics

Most large carnivores produce a suite of common characteristics that defines damage to large mammalian prey skeletons, including humans (Table 9.7). In North America and Eurasia, these large species are most commonly ursids (brown/grizzly bear, black bear [*Ursus americanus*], and polar bear [*U. maritimus*]), large felids (mountain lion/cougar/puma and leopard), large canids (wolves, coyotes, large breeds of domestic dog), and hyaenids (which only include striped hyena [*Hyaena hyaena*] in this range). Sub-Saharan Africa in particular has many species of large and medium-small carnivore, and data derived from these species will be drawn upon. Great overlap in gnawing behavior occurs among medium-small carnivores. The most common ones in North America and Eurasia include smaller canids (most commonly red fox [*Vulpes vulpes*], smaller domestic dog breeds, and black-backed jackal [*Canis mesomelas*]), smaller felids (including domestic cats [*Felis catus*] and lynx), most members of the Mustelidae (weasels, minks, martens, etc.), and a single member of Procyonidae (raccoon [*Procyon lotor*], which have also been introduced to Europe), and their separate characteristics are differentiated where possible.

The commonalities of skeletal destruction by large carnivores (Table 9.7) include a preference for fresh bone, with nutrients in the form of soft tissue still attached and fat/grease contained within. Dry and/or weathered bone devoid of attached soft tissue is generally avoided by carnivores, as it lacks these nutrients. As discussed earlier, gnawing damage tends to be extensive and occurs rapidly. This damage includes the destruction of weaker elements (Hudson 1993), swallowing small elements whole, and destruction of long bone epiphyses through incremental gnawing to access the marrow spaces. The amount of edge polish to exposed long bone margins is high, accompanied by tooth pitting and scoring near margins and on diaphyses, with the latter usually caused by gripping/manipulation. Tooth punctures and furrows also may be present, but these tend to be caused in softer bone (long bone epiphyses and the axial skeleton) and consequently are often destroyed by later gnawing if the carnivores expend ample time on the remains. Dispersal of bones due to carnivore activity is extremely high and can extend from the immediate area of the

Table 9.7 Characteristics of Large Carnivore Interaction with Carcasses/Bodies

- Fresh bone
- Massive removal of soft tissue
- Destruction of long bone epiphyses
- Destruction of more delicate elements (ribs, vertebrae, sternum, etc.) or portions thereof
- Edge polish to exposed margins (rounding; irregular margins)
- Tooth pitting and scoring near exposed margins
- Scoring in other locations (diaphyses) from gripping and manipulating with teeth
- Furrowing of exposed cancellous bone
- May include tooth punctures, though these tend to get erased as more gnawing occurs
- Dispersal of bone tens of meters to kilometers
- May reconcentrate bone in a den or other favored feeding spot
- Damage to surrounding soft tissue may retain visible tooth marks
- Differentiation between gnawing taxa aided greatly by tracks, feces, and presence of distinctive tooth punctures
- Some species live in close proximity with humans (domesticates and those frequenting garbage, including coyotes, bears, etc.)

carcass/body to kilometers away; initial sites of remains deposition can lack any surviving bone whatsoever as carnivores continue to damage and disperse a skeleton (Haynes 1980b, 1982; Kruuk 1972) and transport the remains elsewhere (Carson et al. 2000; Kerbis Peterhans 1990; Kerbis Peterhans and Gnoske 2001; Kerbis Peterhans and Horwitz 1992; Pokines and Kerbis Peterhans 2007).

Four clear rules emerge from cross-comparison of large carnivore consumption of prey:

1. When prey is abundant, carcass utilization (i.e., the proportion of tissue of an individual prey item that is consumed, including the degree to which bones are gnawed) generally decreases. What wolves leave behind at a kill, for example, is much greater when prey is abundant or more easily hunted. An example is feeding upon moose (*Alces alces*) in deep snow conditions where hard pack has formed, and the moose break through while the wolves do not (Mech 1970; Peterson 1977). If the next prey item can be killed by the wolf pack, they tend to abandon the previous prey item more quickly, use less of it (i.e., leave more bones behind), or return to it less often.
2. Juvenile prey, including humans, are far more quickly and completely destroyed relative to adult remains of that same prey species (Morton and Lord 2006; Pokines and Kerbis Peterhans 2007). Even taxa that are not noted bone gnawers (such as the felids and ursids) can leave very little trace behind of juvenile prey.
3. Seasonality affects carcass utilization in some climates (Keyes et al. 2020). Large carnivores consistently show less interest in frozen carrion that they have found vs. fresh prey that they have killed in winter. This means that heavy utilization of frozen remains is often delayed until the spring thaw, although winters relatively poor in game will mean an increase in frozen carcass utilization. It also may not be possible to access all of a frozen carcass (Haynes 1982; Sorg et al. 2012).
4. As the number of large carnivores feeding increases, carcass utilization increases (Haynes 1980b), including the amount of bone damage (Haynes 1982; Pobiner 2007:113). This scenario is especially relevant to pack animals (as is typical among canids).

When combined, these rules indicate that except under specialized conditions, drawing conclusions about the postmortem interval (PMI) using only the degree to which a set of remains has been consumed by large carnivores can be very tenuous (Haglund et al. 1989). It is clear that consumption of remains can be very rapid, occurring over the course of hours or just a few days in order to render the remains of large prey (including humans) down to very few traces still at the point of initial deposition.

Distinguishing Among Carnivore Bone Gnawers, Large and Small

Numerous studies have attempted to discriminate among species based on the damage caused by large carnivore families (canids, ursids, and felids) typically encountered in North America and other avid bone gnawers (hyaenids) (Andrés et al. 2012; Carson et al. 2000; Delany-Rivera et al. 2009; Domínguez-Rodrigo and Piqueras 2003; Faith and Behrensmeyer 2006; Fisher 1995; Haglund et al. 1988; Haynes 1983; Miller 1969, 1975;

Murmann et al. 2006; Payne 1983; Pobiner 2007, 2008; Pobiner and Blumenschine 2003; Pokines and Kerbis Peterhans 2007; Richardson 1980). Carnivore species differentiation has several inherent difficulties, which include the following: (1) the general dental size overlap among these taxa, (2) the conical shape of canines, allowing them to leave tooth punctures of very different diameters, even when caused by the same individual bone gnawer, (3) the other multiple congruencies in dental morphology among these taxa, especially as their teeth undergo age-related attrition, (4) the effects of repeat damage, where new gnawing damage overlaps with, obscures, or destroys previous gnawing damage, (5) the infinite attack angles available to a bone gnawer when gnawing a bone, (6) the inherent problem that the portions of a gnawed bone most likely to preserve a tooth puncture potentially identifiable to the creating taxon are the least durable and therefore the least likely to survive continued gnawing and other postmortem destructive forces, (7) the possibility that more than one scavenging species gnawed on a bone, and (8) the bone dispersal that typically accompanies large carnivore bone gnawing. As Haynes (1983) noted, bones only lightly gnawed upon by a lion will be indistinguishable from bones only lightly gnawed upon by a bear. In addition, the use of other information such as field signs left behind by the scavengers (Einarsen 1956), including their droppings (Gilmour and Skinner 2012; Murad 1997), or the exclusion of other scavengers in an indoor setting (Steadman and Worne 2007) can aid greatly in differentiating among the species that may have interacted with a set of remains.

In terms of pure destructive force to bone, hyaenids represent the worst-case scenario of skeletal damage and dispersal in terrestrial environments (Kerbis Peterhans and Horwitz 1992; Kruuk 1972; Pobiner 2007; Pokines and Kerbis Peterhans 2007). Fortunately for forensic practitioners in the New World and Europe, these species' extant range is only in Africa and southern Asia. Spotted hyenas (*Crocuta crocuta*) are the most destructive of these, having evolved both as an efficient social hunter and as a scavenger in Africa (Kruuk 1972). Other species, such as wolves, can achieve the overall effects of hyena ravaging to a carcass by taking more time to reach the same results. Since many hours or days are a common interval between death and discovery of remains, large scavenging carnivores often have ample time during the early PMI to gnaw upon remains until they have lost interest and abandoned them. If this takes more time because they are less efficient bone gnawers, then the gnawing efficiency of the taxon involved is unlikely to be discernible through forensic analysis of the overall state of gnawing damage and dispersal.

Figure 9.18 illustrates the great degree of overlap between large and small carnivore behavior, in this case unfused freshly butchered pig humeri gnawed on by a large (26 kg) and small (9 kg) domestic dog. In the case of the former, gnawing occurred for 24 min, and for the latter gnawing occurred for approximately 2 h. The gnawing by the small dog progressed much further, destroying more of the proximal end and involving the distal end. Each individual left behind furrowing in the cancellous bone, edge polish of the cortical bone, and multiple pits and striations, but the large dog left behind no clear marks so large that they could not have been created by the dentition of the smaller dog. While data are limited, other small carnivores can damage large vertebrate skeletons to significant degrees (pers. obs.). Even domestic cats have been demonstrated to leave minor damage on the weaker areas of large vertebrate bones (Moran and O'Connor 1992), although the large vertebrate remains in their experiment were both unfused and cooked, leaving them weaker than uncooked adult bones. Garcia et al. (2020) did not find feral cats to produce significant bone damage to human remains outdoors after limited observations, but under

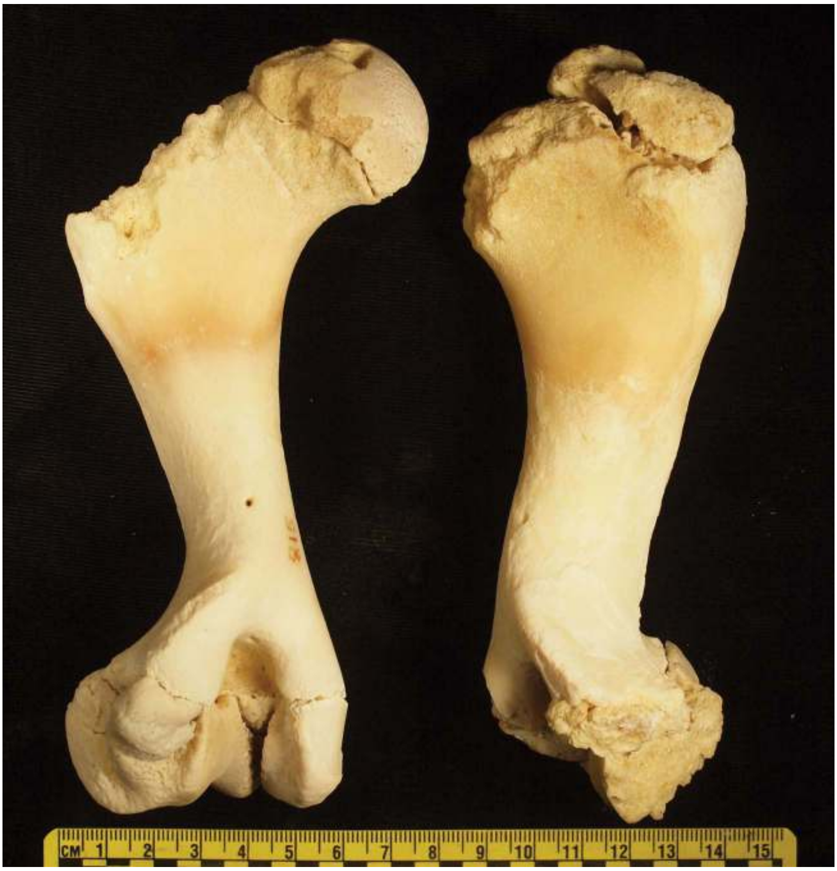

Figure 9.18 Juvenile pig humeri gnawed on by domestic dogs (*Canis familiaris*). Left: gnawed for 24 min by a large (26 kg) dog, damaged on the proximally only; right: gnawed for approximately 2 h by a small (9 kg) dog, damaged proximally and distally. Smaller dogs can cause amounts and types of damage similar to that of large dogs if given longer periods to gnaw, and the differences in gnawing duration will be largely undetectable during common forensic PMIs (days or weeks). (Detached epiphyses have been glued to their original locations after cleaning.) The scale is in cm.

experimental conditions Cohen and Kibii (2015) found that the medium-sized felid caracal (*Caracal caracal*) can leave significant markings on at least rabbit-sized prey.

Other small or medium species have been less well researched regarding their bone altering activities. King et al. (2016) found that Virginia opossum (*Didelphis virginiana*) were capable of at least minor bone alterations to large vertebrate (pig) carcasses, including splintered and fractured rib ends, tooth marks including punctures on scapulae, and removal of a mandibular condyle. Pokines and Pollock (2018) examined the broader small scavenger guild, including birds and small mammals, in a largely forested area in Massachusetts, USA, using secured, isolated, fresh pig long bones. They found that fisher (*Martes pennanti*) could gnaw away significant portions of long bone epiphyses (Figure 9.19) despite the relatively small size of this mustelid species. The margins of the missing bone were crenellated and had few isolated tooth marks, likely due to the small mouth size being unable to fit around bone easily, but small amounts of puncturing and furrowing were present. No other scavenging species registered gnawing on the fresh bones used in that experiment despite the many that consumed adhering soft tissue (Table 9.8). Synstelien (2015)

Figure 9.19 Unfused pig (*Sus scrofa*) femurs, (top) proximal and (bottom) distal, gnawed by fisher (*Martes pennanti*) (Pokines and Pollock 2018). Some areas of (a) furrows and (b) a tooth puncture are visible on the head. Some (a) furrowing is also visible distally. The scale is in cm.

found that many scavengers fed upon human soft tissue of bodies exposed at the University of Tennessee Body Farm in Knoxville, TN. These included raccoon, Virginia opossum, brown rat (*Rattus norvegicus*), and white-footed mouse (*Peromyscus leucopus*). Raccoon produced only small areas of bone modification despite their extensive scavenging of soft tissues, but these modifications were frequent. Hands and feet were the most common sites affected and included the removal and crenellation of small bone extremities. Arms also were a popular location for soft tissue feeding, and tooth marks were most frequent on the distal humeri and proximal ends/shafts of the ulnae. Short striations were common, and some removal of cancellous bone occurred. Raccoons produced rib breakage and crenellated ends and damaged other bone margins. Only small amounts of bone modification were attributable to opossum, including crenellation, tooth polish, and short striations to a medial clavicle.

Research into the scavenging of human remains must consider the entire suite of species utilizing that resource in a given environment. Examining scavenger activity under anything approaching natural conditions encounters the inherent difficulty of separating out the activity of multiple species. Captive studies are only a partial answer (Udoni 2019; Udoni et al. 2021), as the activity of captive animals likely differs from those of their wild counterparts, especially in the amount of time that can be devoted to gnawing on a single bone when a full diet is readily supplied.

Overall Skeletal Damage and Locations

Table 9.9 compares the amount of skeletal damage caused to large vertebrates from multiple studies of large carnivores worldwide to different classes of large mammalian prey, including humans. The weaker elements or portions thereof with thinner cortical bone (including vertebrae, sterna, ribs, and pelves) underwent greater amounts of destruction, regardless of which large carnivore taxon was doing the gnawing. Smaller durable bones such as carpals may still be damaged or lost by being consumed whole and deposited elsewhere. There is enough overlap among all of these predators that determination of which taxon has scavenged a partial set of remains is extremely difficult when simply relying upon the degree of scavenging. For example, while hyenas tend to destroy and transport away more of a large vertebrate skeleton than other large terrestrial scavengers, the same skeleton may reach a similar (and indistinguishable) degree of damage when scavenged by other taxa for a longer duration or by more individuals (i.e., equifinality of taphonomic effects). Canids tend to be the next most destructive to skeletons, likely due in part to the commonness of pack instead of individual behavior. Ursids and felids tend to damage vertebrate skeletons to lesser degrees among the taxa presented in Table 9.9, with suids the least damaging. Large carnivores also can consume small prey whole, leaving highly fragmented and partially digested bones in feces (Lloveras et al. 2020).

Carson et al. (2000) suggested that overall human skeletal representation left at a scene of initial deposition may help to separate the scavenging action of black bears vs. large canids in their study area in New Mexico, USA. The largest difference that they noted in skeletal recovery from multiple cases ($n = 7$) of likely black bear scavenged remains is a reduced recovery of vertebral elements and sterna when compared with the canid scavenging pattern on human remains found by Haglund et al. (1989) in the Pacific Northwest. Overall elemental damage was comparable, with preferential attack of the long bone epiphyses to reach the marrow cavities and general attack upon the softer elements (scapulae, innominates, etc.). Note that this difference, if real, also holds true if the vertebral and sternal elements were transported away from the immediate scene for later consumption elsewhere or consumed on the spot. The effects of the more marginal environment in the bear study area (desert uplands) are unknown, in that greater carcass utilization may hold where scavengeable remains are scarcer. In contrast, Willey and Snyder (1989) found a very high degree of vertebral consumption/destruction of the carcasses of white-tailed deer fed to five captive wolves, which had greater time to consume each carcass fully.

Table 9.8 **Mammalian Scavenger Guild, Holliston, Massachusetts, USA**

Common Name	Taxon	Day with Contact	Night with Contact	Day No Contact	Night No Contact	Total Visits	% Total Visits
Mammal Taxa Not Detected Contacting Bone							
Coyote	cf. *Canis latrans*	0	0	0	1	1	0.2
Groundhog	*Marmota monax*	0	0	4	0	4	0.8
White-tailed deer	*Odocoileus virginianus*	0	0	4	1	5	1.0
Gray fox	*Urocyon cinereoargenteus*	0	0	1	1	2	0.4
Unknown mammal		0	0	0	1	1	0.2
Unknown small mammal		0	0	1	1	2	0.4
Mammal Taxa Detected Contacting Bone							
Virginia opossum	*Didelphis virginiana*	0	16	0	15	31	6.3
Northern short-tailed shrew	*Blarina brevicauda*	2	2	0	2	6	1.2
Striped skunk	*Mephitis mephitis*	0	6	0	15	21	4.3
Long-tailed weasel/stoat	*Mustela frenata/erminea*	0	10	1	5	16	3.2
Fisher	*Martes pennanti*	3	4	1	1	9	1.8
House cat	*Felis catus*	1	0	3	0	4	0.8
Raccoon	*Procyon lotor*	0	10	0	15	25	5.1
Deer mouse/white-footed mouse	cf. *Peromyscus maniculatus/leucopus*	0	126	0	114	240	48.7
Eastern gray squirrel	*Sciurus carolinensis*	1	0	29	1	31	6.3
Eastern chipmunk	*Tamias striatus*	55	0	30	5	90	18.3
Unknown medium mammal		0	1	0	4	5	1.0
Totals		**62**	**175**	**74**	**182**	**493**	**100.0**

Source: Pokines and Pollock (2018:55). Used with permission, *Forensic Anthropology*/University of Florida Press.

Table 9.9 **Comparison of Large Carnivore Interaction with Large Vertebrate Remains**

	Domínguez-Rodrigo (1999)	Pobiner (2007)	Pobiner (2007)	Phillips (1993)
Taxa - consumer	Felidae Lion (*Panthera leo*)	Felidae Lion (*Panthera leo*)	Felidae Lion (*Panthera leo*)	Felidae Cheetah (*Acinonyx jubatus*)
Taxa - consumed	Large ungulates	Large ungulates	Small ungulates	Small antelopes and other bovids (30–50 kg)
MNI consumed taxa	n = 28	n = 7	n = 9	n = 24
Location	Kenya	Kenya	Kenya	Namibia
Source	Kill sites	Kill sites	Kill sites	Kill sites
Environment	Savanna	Savanna (game preserve)	Savanna (game preserve)	Savanna
Typical Gnawing Damage				
Crania	Little modification	Modification to face, base, vault	Heavy modification to face, base, vault	Little modification
Mandibles	Little modification	Little modification	Heavy modification	Little modification
Vertebrae	Processes damaged	Processes damaged; sometimes consumed	Processes damaged; sometimes consumed	Processes damaged
Ribs	Distal ends broken	Generally heavy damage	Generally heavy damage	Up to half consumed
Sterna	(No data)	(No data)	(No data)	(No data)
Innominates	Tooth marks on margins	Moderate damage to margins	Heavy damage to margins	(No data)
Clavicles	N/A	N/A	N/A	N/A
Scapulae	Tooth marks	Moderate damage to margins	Heavy damage to margins	(No data)
Long bones	Minor damage on extremities from defleshing	Little-to-moderate damage to epiphyses	Generally heavy damage to epiphyses	Abandoned at feeding sites
Metapodials	Rare tooth marks	Rare damage	Rare damage to epiphyses	(No data)
Carpals/tarsals/ phalanges	Not consumed	Rare damage	Rare damage	Untouched
Aggregation of Bone	Individual kills dragged to shade for feeding	None	None	None

(Continued)

Table 9.9 *(Continued)* **Comparison of Large Carnivore Interaction with Large Vertebrate Remains**

	Simons (1966)	Horwitz and Smith (1988)	Pokines and Kerbis Peterhans (2007)	Carson et al. (2000)
Taxa - consumer	Felidae Leopard (*Panthera pardus*)	Hyaenidae Striped hyena (*Hyaena hyaena*)	Hyaenidae Spotted hyena (*Crocuta crocuta*)	Ursidae Black bear* (*Ursus americanus*)
Taxa - consumed	Baboon (*Papio* sp.)	Human	Large ungulates	Humans
MNI consumed taxa	n = 22	n = 10	n = 151	n = 7
Location	Kenya	Israel	Kenya	New Mexico, USA
Source	Kill site/cave den	Cave dens	Cave den	Scavenged sites
Environment	Savanna	Desert	Savanna	High desert
Typical Gnawing Damage				
Crania	Frequent tooth marks; damage to facial area	Reduced to calvaria	Most reduced to tooth rows	Generally intact; some minor damage
Mandibles	Tooth rows recovered	Tooth rows	Most reduced to tooth rows	Unmodified
Vertebrae	Few recovered; some damage	None recovered	Frags. only remain	Many destroyed; spinous processes damaged
Ribs	None recovered	None recovered	Frags. only remain	Heavy damage
Sterna	None recovered	None recovered	All destroyed	All destroyed
Innominates	Margins removed	None recovered	Highly fragmented	Gnawing to margins, tooth marks
Clavicles	None recovered	None recovered	N/A	Frequently modified or unrecovered
Scapulae	Margins gnawed	None recovered	Glenoid and frags. remain	Frequently modified or unrecovered
Long bones	Most epiphyses gnawed off	Shafts only recovered	Weakest epiphyses consumed, many reduced to cylinders	Weakest epiphyses consumed
Metapodials	Few recovered	None recovered	Weakest epiphyses consumed, many reduced to cylinders	Few recovered
Carpals/tarsals/ phalanges	Few recovered	None recovered	Often consumed	Few recovered
Aggregation of Bone	Significant at feeding sites	Maximal among extant taxa	Maximal among extant taxa	Limited

(Continued)

Table 9.9 *(Continued)* **Comparison of Large Carnivore Interaction with Large Vertebrate Remains**

	Arilla et al. (2014); Roselle et al. (2019)	Haynes (1980b, 1982)	Haynes (1980a)	Haglund (1997a)
Taxa - consumer	Ursidae Brown bear (*Ursus arctos arctos*)	Canidae Wolf (*Canis lupus*)	Canidae Wolf (*Canis lupus*)	Canidae Coyote and dog (*Canis latrans, C. familiaris*)
Taxa - consumed	Large ungulates	White-tailed deer (*Odocoileus virginianus*), bison (*B. bison*), moose (*Alces alces*)	White-tailed deer (*Odocoileus virginianus*)	Humans
MNI consumed taxa	n = 17	N/A; general observations	n = 94	n = 53
Location	Spanish Pyrenees	Canada and Minnesota, USA	Minnesota, USA	Pacific NW, USA
Source	Kill/scavenge sites	Kill/scavenged sites	Fall/Winter kill/ scavenged sites	Scavenged sites
Environment	Montane	Boreal forest/ wetlands	Mixed forest	Boreal forest
Typical Gnawing Damage				
Crania	Frequent tooth marks	Juvenile crania often destroyed; damage to weaker areas	Often removed; damage from only to weaker areas to only tooth rows left	Damage to weaker areas (face, etc.)
Mandibles	Few recovered	Light damage	Often removed; variable damage	Variable damage
Vertebrae	Significant damage	Frequent damage to processes; often removed/destroyed	Frequent damage to processes; often removed/destroyed	Frequent damage to processes; often destroyed
Ribs	Significant damage	(No data)	Often removed; heavy damage	Frequent damage; often destroyed
Sterna	Few recovered	(No data)	Usually completely splintered/consumed	Often removed/destroyed
Innominates	Tooth marking, crushing	Gnawing to margins	Gnawing to margins; often only acetabulum remains	Gnawing to margins/ removed
Clavicles	N/A	N/A	N/A	Often removed/destroyed
Scapulae	Few recovered; tooth marks	Gnawing to margins	Often removed; gnawing to margins	Gnawing to margins
Long bones	Tooth marks	Weakest epiphyses consumed; gradual reduction to cylinders	Weakest epiphyses consumed to greater damage noted	Weakest epiphyses consumed; gradual reduction to cylinders
Metapodials	(No data)	Proximal damage common	Lower legs often all remaining at kill site	Frequently missing
Carpals/tarsals/ phalanges	(No data)	(No data)	Lower legs often all remaining at kill site	Frequently missing
Aggregation of Bone	None	Not noted	Not noted	Not noted

(Continued)

Table 9.9 *(Continued)* **Comparison of Large Carnivore Interaction with Large Vertebrate Remains**

	Domínguez-Solera & Domínguez-Rodrigo (2009)
Taxa - consumer	Suidae Pigs (*Sus scrofa*)
Taxa - consumed	Partially disarticulated lamb (*Ovis aries*), cattle (*Bos taurus*) and pigs
MNI consumed taxa	N/A
Location	Spain
Source	Captive and wild feeding
Environment	Farm and forest
Typical Gnawing Damage	
Crania	(Not tested)
Mandibles	(Not tested)
Vertebrae	Most consumed completely
Ribs	(Not tested)
Sterna	(Not tested)
Innominates	Most consumed completely
Clavicles	N/A
Scapulae	Margins gnawed
Long bones	Tooth marks including incisal furrowing on epiphyses
Metapodials	Some swallowed whole
Carpals/tarsals/ phalanges	(Not tested)
Aggregation of Bone	None

* Some canid involvement could not be ruled out.

Indoor Effects

The indoor isolation of domesticated carnivores with a human body can lead to high degrees of damage to bone if there is a long interval between death and discovery. Steadman and Worne (2007) noted that canid scavenging of human remains in a confined, indoor setting over an interval of multiple weeks can leave very few identifiable osseous remains behind. In this case, the two dogs had exhausted their other food options and had to consume their former owner to survive a long period unattended. Galté et al. (2014) also noted extensive postmortem scavenging in an indoor setting, including damage to vertebrae, ribs, and some long bones, including turning the right humerus into a cylinder; dismemberment included the skull and right foot. Colard et al. (2015) reviewed multiple new cases from New York City (n = 31), Lille, France (n = 10), and previously published cases (n = 22) regarding postmortem feeding upon humans by domesticated dogs in indoor settings. The postmortem intervals ranged from less than one day to weeks. They found that tooth marks were present on bone in 26.9% of the cases and appeared at earliest 24 hours after death, but other cases with gnawed bones did not occur until at least one week after death. Scavenging in general began most frequently with the face, regardless if the decedents were clothed.

Dental Arcade Bite Pattern and Size

An impression of all or a portion of the gnawing species' dental arcade may narrow down which taxon has scavenged remains. Repeated gnawing of the same area obscures clear bite mark impressions, and most bone areas are generally too dense to leave a clean impression of multiple teeth crushing inward all at once. Exceptions include ribs, innominates, and scapulae. Bite force is also at the minimum, since the impressing teeth most often are in the anterior apex of the dental arcade and farthest from the fulcrum point at the TMJ (Figure 9.3). For this reason, clear bite mark patterns are more likely to be found in soft tissue (Lyver 2000) or associated articles of clothing. In addition, since the canines are much longer and larger than the incisors in all of these species, these teeth are far more likely among the anterior teeth to leave an impression behind in bone.

The great overlap in carnivore species' dental arcade size also makes this determination difficult: the number of anterior teeth in each case is the same: three incisors and the canine in each quadrant. If a larger portion of the dental arcade than just the canines leaves an impression, the overall pattern is more distinctive. Murmann et al. (2006) measured intercanine distances and made impressions of the common North American (~the Nearctic) scavengers. They noted clear differences by carnivore family (Ursidae, Canidae, Felidae, and Mustelidae) in anterior arcade shape. Felids were distinctive in their flat, long row of incisors, with an intermediate amount of curvature for ursids and mustelids and the greatest amount of anterior curvature among canids. Their study also included juveniles and had large samples for each species, drawing upon a number of available subspecies. Murmann et al. (2006) found large amounts of overlap in intercanine width among and between Carnivore families, although the larger species can be separated from the smaller using their data.

Tooth Mark Morphology and Size

Tooth mark morphology and size may indicate a single carnivore or class of carnivores, especially when the known types of carnivores in an area are restricted to fewer viable options. Pobiner (2007) studied multiple species of African carnivore (lions, spotted hyenas, leopards, cheetahs, and jackals) and their interaction with many sizes of large non-human mammal in both a game park and an animal rehabilitation facility. This research included noting the type of tooth mark and maximal dimensions. She found that while all of these carnivores left tooth marks that are relatively small in size, only the largest two species (lions and spotted hyenas) left large tooth marks. Andrés et al. (2012) similarly noted a great deal of overlap of the measured lengths of tooth pits left on long bone ends by the range of gnawing species that they studied, including large and small carnivores and humans. They found that statistically significant separation could be achieved only for the very largest gnawers (spotted hyenas and lions) vs. the other species. Other distinctions among smaller gnawing taxa may be possible using additional dimensions measured for tooth pits. Differences in markings were also more distinctive when the gnawed-upon species was adult/larger, and the bones were not so easily destroyed by gnawing (Andrés et al. 2012). Young et al. (2015b) found that tooth pit dimensions helped distinguish red fox (*Vulpes vulpes*) from Eurasian badger (*Meles meles*) and domestic dog, but not between those of badgers and dogs. Large scavengers therefore may leave behind individual tooth marks that are too large to have been created by small scavengers, despite the great deal of overlap normally encountered.

Grading Overall Levels of Carnivore Gnawing Damage

Pobiner et al. (2020) provided a scale to grade the amount of gnawing damage to a given bone, developed from previous research on modern scavengers in East Africa (Pobiner and Blumenschine 2003) of modern lion kills and subsequent feeding upon zebras (*Equus quagga*). Their scale, however, is broad enough to be adapted to any species gnawing upon human bones, as only the general amount of damage to a given bone needs to be assessed. It also is to be expected that some large species consistently would inflict damage at the upper end of the scale that is not found commonly among forensic cases. The Pobiner et al. (2020) scale proceeds as: (0) no damage; (1) tooth marks only with no significant loss of bone; (2) minimal chewing damage, often consisting of loss of margins; (3) moderate chewing damage, including partial loss of epiphyses of long bones; and (4) severe chewing damage, fragmentation, or destruction, which can result in long bones being reduced to cylinders. More uniform data collection among forensic cases and experiments may lead to a more robust source of comparative data, and grading options such as this should be tested for human skeletons and employed.

Pig Gnawing Characteristics

Domestic and feral pigs (*Sus* spp.) are avid omnivorous scavengers, which will include animal protein in their diet when available, including human and other large primate tissues (Berryman 2002; Galdikas 1978; Greenfield 1988; Wilcox and Van Vuren 2009). Their interactions with large mammal carcasses are similar in some respects with large carnivores, although their teeth are neither adapted to bone crushing nor particularly effective at soft tissue shearing (Hillson 1986). Contrary to what has reached popular myth status, pigs cannot consume an entire human skeleton and leave little trace. Their ubiquitous presence throughout the world in urban, rural, and wilderness settings, however, increases their taphonomic significance (Greenfield 1988). This species, along with domestic/feral dogs, are in many ecosystems throughout the world the largest terrestrial scavengers, such as in Australia, Papua New Guinea, the Hawaiian Islands, other geographically isolated locations, and physically enclosed local ecosystems (i.e., pig farms).

Berryman (2002) described a case of probable pig scavenging of a human in Tennessee, USA. The largely articulated body had undergone some skeletal scavenging and displayed postmortem damage predominantly upon the more delicate portions: the facial area, vertebral column, innominates, and ribs. Additional anterior tooth scoring was noted on a femur, tibia, and both medial clavicles. Much of the thoracic cavity breakage was attributable to the opening of this area to feed upon viscera and therefore may have been caused more by scavenger mass pressing down than by direct mastication behavior. The overall pattern showed confinement to the softer portions of the body in contrast to the type of feeding and bone damage caused by large carnivores. These results parallel the partially controlled pig-feeding experiments of Greenfield (1988), where domestic pigs were found to destroy smaller, weaker isolated large mammal elements (vertebrae and sacrum) and leave some gnawing damage on long bone epiphyses (Figure 9.20). Berryman (2002) noted that parallel scoring caused by the lower incisors may be indicative of pig scavenging. Other damage and some missing elements indicate that other scavenger involvement with these remains was possible, but the proximity of domesticated pigs indicated that most damage likely was caused by them. This individual was dead for a maximum of 10 days, which indicates a much lower overall rate of scavenging, osseous damage, and dispersal by the pigs relative to large carnivores.

Experimental feeding experiments among *Sus* taxa (Domínguez-Solera and Domínguez-Rodrigo 2009) generally indicate an ability among pigs to consume/destroy weaker elements (scapulae, vertebrae, and innominates) and modify the epiphyses of long bones (femora and tibiae). Whether this represents habitual consumption patterns in the wild when confronted with largely intact carcasses is unknown, as many of the experimental runs involved defleshed and disarticulated elements from pigs, lambs, and cattle. Minor experiments using wild pigs showed a similar pattern of bone destruction: weaker elements modified or consumed and long bone epiphyses gnawed upon with fragmentation of shafts prevalent among smaller elements. Some whole small bones (tarsals) likely were consumed in their entirety. Dispersal was minor, and interest in individual elements by penned animals generally ceased after 1.5 h.

Damage possibly indicative of pig involvement with remains was discovered in the form of broad furrows formed by pig incisors (Domínguez-Solera and Domínguez-Rodrigo 2009:356). This modification is significant in that pigs use their broad, flat incisors for gnawing, whereas the cheek teeth are normally used by most terrestrial carnivores including felids, hyaenids, canids, and ursids. An example of this type of incisor scoring and cancellous bone exposure, including surface peeling, is shown in Figure 9.20. Pigs also show a preference for remains of smaller large mammals, those <50 kg mass, which includes much of the human size range. Bones from larger species including cattle are less heavily modified.

Ungulate Osteophagia Characteristics

Despite numerous references to osteophagia among a variety of ungulate species, this phenomenon has undergone little systematic study, and knowledge of it derives primarily from chance observational reports (Bowyer 1983; Brothwell 1976; Kierdorf 1993, 1994;

Figure 9.20 Damage to bone caused by pig (*Sus scrofa*) gnawing. (Top) blunt, parallel scoring made by the incisors; (bottom) long bone epiphysis with areas of thin cortical bone removed (including some peeling), exposing cancellous bone. (Images courtesy of Dr. Manuel Domínguez-Rodrigo.)

Meckel et al. 2018; Sutcliffe 1973, 1977; Wyatt 1971). The reason for bone consumption is likely a response to dietary mineral deficiencies based upon local environment, so not all members of an animal population will practice bone consumption. Due to the broad occlusal molar surfaces of ungulates that evolved for a herbivorous or omnivorous diet, damage to the bone consists of a battered, ground appearance with heavy tooth pitting. Beginning and intermediate stages of alteration consist of broad, rounded grooves consistent with the broad cusps of herbivores that gradually wear away the bone (Cáceres et al. 2011:2769;

Hutson et al. 2013). Heavy wear leads to a characteristic *Y-fork* shape left on the ends of long bones (Figure 9.21). Given the number of potential osteophagic taxa involved throughout the world, a high degree of variation is expected, and this specific taphonomic feature may be difficult to identify especially in its early stages. North American ungulate species that are potential bone gnawers, apart from domesticated taxa, include white-tailed deer (Meckel et al. 2018).

Figure 9.21 Damage to a white-tailed deer (*Odocoileus virginianus*) metapodial caused by intraspecies osteophagia, Massachusetts, USA. Note the characteristic Y-fork shape to the end. The scale is in cm.

Table 9.10 Characteristics of Large Rodent (e.g., Porcupine) Interaction with Bone

- Dryer, weathered bones are preferred
- Transport of larger elements to a den is typical of some species
- Tend to sample all bone sources in home area regardless of taxon
- Damage caused (parallel striations) is similar to that caused by smaller rodents, but more damage than is typical of the latter
- Incisor sharpening and nutrient ingestion of the dry bone
- Not known to scavenge fresher bones/carcasses to consume soft tissue
- Repeated gnawing often obliterates distinct furrows, leaves behind a more even margin
- Porcupines normally avoid human contact and are excluded from many scenes of potential forensic interest

Porcupine and Other Large Rodent Gnawing Characteristics

Among large rodents, porcupines (most commonly North American porcupine *Erethizon dorsatum* and *Hystrix* spp. in Africa and southern Eurasia) are the most avid bone gnawers (Kerbis Peterhans 1990; Roze 2009) (Table 9.10). *Hystrix* is also an avid bone collector, concentrating large amounts in den sites. This extreme behavior regarding bones has not been detected in the repertoire of other large rodents, although relatively little study has been performed in this area. Porcupines have broad upper and lower incisors and leave broader, flatter (and deeper) gnaw marks upon bone than smaller rodents. Their wider marks (Figure 9.22) are concentrated on the margins of elements, and repeated gnawing often obliterates distinct individual marks, leaving behind a more even margin. They leave similar marks behind on wood, especially on objects where perspiring human hands have

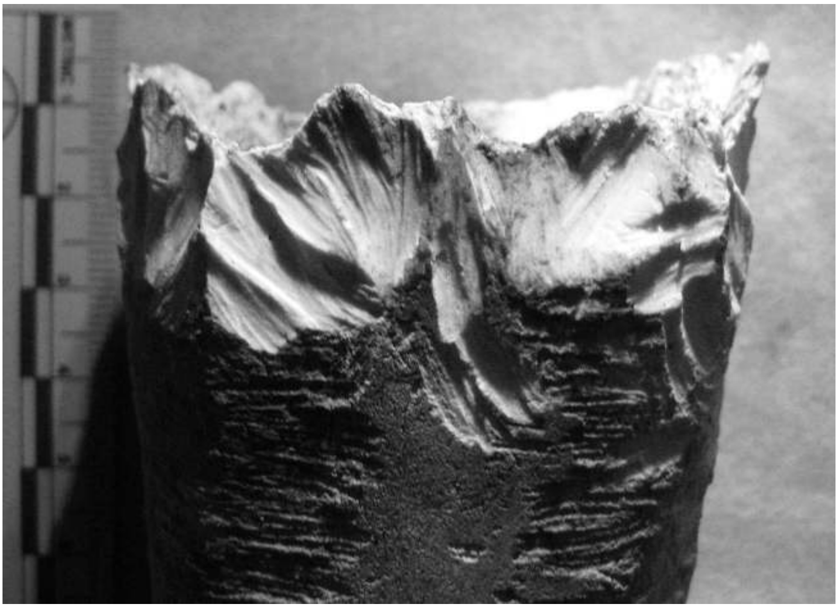

Figure 9.22 Large rodent gnawing (North American porcupine, *Erethizon dorsatum*) upon dry, weathered large mammal bone. Note the irregular sculpting of the upper margin and the sets of more regular, shallower, and older convergent striations below. The scale is in cm.

touched repeatedly (tool handles, door frames, etc.) and left behind salts (Roze 2009). They do not normally seek out fresher remains, as they are otherwise herbivores, although Roze (2009) does report an isolated instance of North American porcupine feeding upon the bones from the remains of a fresh white-tailed deer (*Odocoileus virginianus*). The majority of this gnawing behavior is dietary in nature, in order to increase sodium intake in otherwise low-sodium environments (Duthie and Skinner 1986; Roze 2009).

Denning behavior differs between these two ubiquitous genera. Concentration of bones within dens has not been reported for *E. dorsatum* (Betancourt et al. 1986; Roze 2009). In the northeastern United States, for example, dens of *E. dorsatum* are normally occupied only in winter for the thermal benefits (Roze 2009). Food is not transported to dens, and the vegetal remains that may build up there are almost entirely derived from fecal matter (Betancourt et al. 1986). It is, of course, possible that bones already transported to a den that is used by other species may be gnawed upon later in that location by *E. dorsatum* (Dixon 1984). *Hystrix*, in contrast, are avid bone transporters (Alexander 1956; Kerbis Peterhans 1990). They tend to sample all bones (above a certain size, avoiding smaller mammal bones) indiscriminately within their home ranges.

Porcupines as indicated above show a marked preference for dry/weathered bone as opposed to fresh, greasy bone. Data from the mixed spotted hyena/*Hystrix*-accumulated sample in Masai Mara Cave, Kenya (Pokines and Kerbis Peterhans 2007), show a clear trend for the weathered bones to have been gnawed by porcupines while the unweathered, fresh bones were collected and gnawed by the hyenas. Of the 31 identified skeletal elements with porcupine gnawing in this sample, 15 (48.4%) had reached weathering stages 1–4 (i.e., at least mostly degreased), compared with 7.3% of the total sample, a statistically significant difference (chi square = 70.56, $p \leq 0.001$, d.f. = 1). Brain (1981) noted similar results among osseous remains collected from another recent porcupine den in South Africa (Nossob): only 15 of 1620 osseous elements (0.9%) retained residual grease. This weathering state corresponds with stage 0, with the remaining 99.1% falling into stage 1 or higher. Of course, any given skeletal element encountered during a forensic investigation could first have undergone gnawing by a carnivore, then abandonment, followed by drying out and weathering, then gnawing and possibly transport by a porcupine. This sequence of events may be determinable by the weathered state of the residual carnivore gnawing marks, with fresher traces of porcupine gnawing.

Small Rodent Gnawing Characteristics

Small rodents present two separate suites of characteristics when interacting with skeletal remains. The better known of the two is gnawing upon dry bone (see below). This behavior is exhibited by many species of rodent and likely by many that have not yet been studied in this regard, since over 2200 species of rodent have been described (over 40% of all mammal species) (Wilson and Reeder 2005). Omnivorous rodents (in forensic terms, most importantly black rats [*Rattus rattus*] and Norway rats [*R. norvegicus*]) also will consume fresh remains and gnaw into fresh bone while doing so (Haglund 1992, 1997b; Klippel and Synstelien 2007; Patel 1994; Synstelien 2015; Tsokos et al. 1999). Other rodents less well known for omnivory include eastern gray squirrel (*Sciurus carolinensis*), chipmunk (*Tamias striatus*), and wood mice (*Apodemus sylvaticus*) (Pokines and Pollock 2018; Young et al. 2014). Rodent involvement with human remains even goes so far as nesting within them and feeding upon soft tissue (Haglund 1992; Synstelien 2015:155; per. obs.) or gnawing upon dry bones (Pokines 2015; Pokines et al. 2017). Given their cosmopolitan distribution, avid feeding activity, sometimes local abundance, commensalism, the potential exclusion of scavenging vertebrate competitors from many indoor death scenes, and the frequency in which increasing human social isolation leads to deaths going unreported or unnoticed for months or years, the forensic importance of these taxa is greatly increased.

Fresh Remains

The characteristics of small rodent gnawing upon fresh remains are presented in Table 9.11, in contrast with their gnawing patterns upon dry bone, and the commonalities in these two behaviors. These two modes of behavior (i.e., *wet-bone gnawing* vs. *dry-bone gnawing*) also likely have areas of overlap, such as gnawing upon remains in the early PMI that are largely defleshed and retain their greasy texture. One set of remains in isolation also may pass from perimortem/recent postmortem involvement by rodents and slowly into later postmortem involvement, as the remains decompose and receive continued rodent feeding attention (see below). In addition, one species of omnivorous rodent (spiny mouse, *Acomys cahirinus*) found in Egypt and neighboring areas is known to nest in archaeological sites and causes recent gnawing damage on the dried external soft tissue and marrow of mummies (Osborn and Helmy 1980:299). Commonalities in these two modes of behavior include a general inability or disinclination to disperse remains from their point of origin, the main exception

Table 9.11 Characteristics of Small Rodent Gnawing on Fresh Remains and Dry/Weathered Bones

Fresh Bones/Bodies/Carcasses	Dry/Weathered Bones
• Primary purpose: consumption of nutrients • Consume soft tissue and continue into delicate bone areas (epiphyses, nasal margins, etc.) • Adjacent soft tissue not typically penetrated, unlike carnivores • Leave behind pedestaled areas of bone when gnawing into epiphyses • Fresh bone consumption therefore more likely from an omnivorous small rodent taxon • See Haglund (1997b)	• Primary purposes: incisor sharpening and consumption of nutrients • Often will gnaw wood or other hard objects in the same manner • Leave behind short, parallel striations • Often prefer sharp margins of dense bone • Striations single row (mandibular incisors engaged while maxillary incisors hold the bone in place) or convergent row (both sets of incisors converge at a point) • May be a caused by a variety of small rodent taxa (rats, squirrels, voles, gerbils, etc.)
Characteristics Common to Both	
• Tend not to disperse large elements very away from initial area of deposition • (Exceptions: wood/pack rats [*Neotoma* spp.] will transport and concentrate small elements or fragments; burrowing by many species will displace buried bones.) • Marks on bones lack associated pits, punctures, and striations characteristic of carnivore gnawing (note: it is common for bones in many terrestrial environments to have both carnivore and rodent gnawing—Chapter 20) • Uniform pitch and parallel damage to bone margins (carnivore margins crenellated, may form edge polish) • Other: presence of rodent droppings or live rodents themselves (less likely to be frightened away immediately by human presence) • Other: exclusion—some scenes allow only rodent access to a body, such as house interiors	

Figure 9.23 Rodent wet-bone gnawing into phalanges. The gnawing has left behind undamaged proximal ends (i.e., pedestaling) as the bone was tunneled into. Only a species with a narrow snout could cause such damage without damaging much more the adjacent bone or removing the end entirely. The scale is in cm.

being wood/pack rats (*Neotoma* spp.), which are found mostly in the western United States and northern Mexico but also extend into the eastern United States and Canada (Betancourt et al. 1990). Burrowing behavior by a multitude of rodent species, however, can accidentally disturb buried remains in most world locations and cause significant bone displacement. Rodent gnaw marks, in contrast to those of carnivores, consist of fine parallel grooves confined to smaller surfaces that they can fit into their relatively small mouths. Their gnawing also lacks the associated pits and other damage away from the main areas of damage concentrated on bone margins, unlike carnivore damage, which normally encompasses more of a given bone. Rodent involvement also may be indicated by their ubiquitous droppings or fur at a scene and by the exclusion of access by other possible scavengers (closed buildings, etc.).

Small rodent gnawing on fresh remains includes the recently deceased, so a great deal of soft tissue damage may occur (Haglund 1997b; Patel 1994) and without any bone involvement (Tsokos et al. 1999), especially when competing scavengers are excluded from a death scene. Soft tissue damage is normally confined to exposed areas, so faces and hands often receive the most attention. Gnawing of soft tissue often continues into the osseous tissues, especially thin margins of bone (such as the nasal region) or into softer bone (the epiphyses). In the latter case, *pedestaling* can occur (Figure 9.23 and 9.24), where an epiphysis is gnawed into, leaving areas of untouched bone adjacent to the damaged location. (Note that small carnivores potentially may cause pedestaling, although they tend to leave much more ragged margins and cause other kinds of tooth damage elsewhere on the same

Figure 9.24 Rodent wet-bone gnawing into a distal left radius, (left) anterior and (right) posterior aspects. The gnawing has left behind an undamaged distal end (i.e., pedestaling) as the bone was tunneled into. Only a species with a narrow snout could cause such damage without damaging much more the adjacent bone or removing the end entirely.

Figure 9.25 *Rattus* sp. gnawing on the spinous process of a pig (*Sus scrofa*) thoracic vertebra. The bone was still greasy, and the gnawing appears to have targeted the fat content as a resource. The scale is in cm.

bone.) Fine parallel striations are still found on the margins of cortical bone gnawed by small rodents (Figure 9.25) where these bones are still greasy, and the activity appears to have been directed at least partly at extracting the fat resource.

Dry/Weathered Bone

Rodent damage to dry/weathered bone (Table 9.11) often has the ultimate cause of incisor sharpening instead of nutrient ingestion, although multiple species of small rodent consume dry bone for the mineral nutrient content (Carlson 1940; Coventry 1940). Small rodents leave similar gnaw marks on wood and other hard materials, including plastic. Due to their size, they tend to attack preferentially the thinner, exposed margins of bones, such as long bones where the epiphyses have already been removed by other processes (carnivore action, weathering, etc.). The striations left behind can be of two types: *singular*, where only the maxillary or mandibular paired incisors have been dragged across the surface while the other holds the bone steady, and *convergent*, where the maxillary and mandibular incisors are used simultaneously to drag against the bone while converging on each other (Figure 9.26). When the gnawing motion primarily is to hold the bone in place with the maxillary incisors while moving the mandibular incisors, the maxillary incisors may leave shorter striations termed *anchor marks* (Figure 9.27). The distinctive, parallel

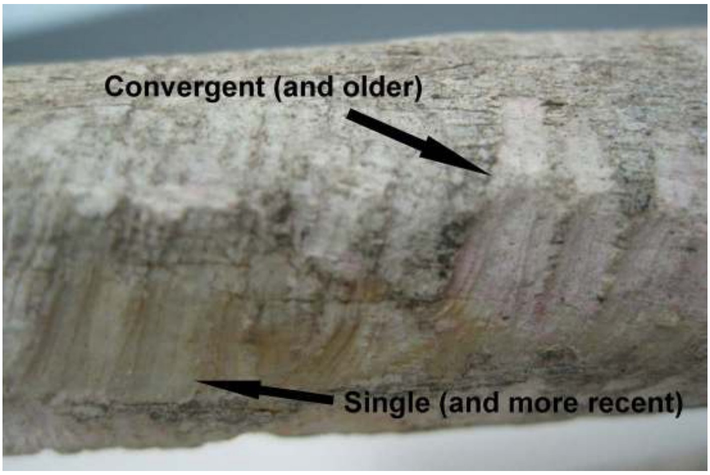

Figure 9.26 Rodent dry-bone gnawing on a tibia, showing convergent tooth marks, where the maxillary and mandibular incisors were used at the same time, and single tooth marks, where only the mandibular incisors were used. The single marks are more recent, as they have exposed bone with its natural, unbleached color.

Figure 9.27 Rodent dry-bone gnawing on an innominate, showing anchor marks (white arrow) where the maxillary incisors gripped the bone and (black arrow) striations formed by the mandibular incisors moving against the bone. Some paired striations are visible, where the two adjacent mandibular incisors can be seen marking the bone in parallel. The scale is in cm.

Figure 9.28 Rodent dry-bone gnawing on cranial elements. Top: thin areas of the face sculpted by repeated gnawing; bottom: disarticulated portion of cranial vault with the margin gnawed.

markings are difficult to confuse with other kinds of taphonomic observations and can appear on cranial (Figure 9.28) or postcranial (Figure 9.29) elements, especially thin margins, often removing previous surface staining and exposing pale underlying bone.

The width of the markings varies according to rodent incisor size, although there is a great deal of overlap among taxa. Pokines et al. (2017) measured the incisor maxillary (Figure 9.30, top) and mandibular (Figure 9.30, bottom) occlusal plane widths for all extant rodent and lagomorph (rabbits, etc.) species found in Massachusetts, USA, including invasive species (rats, etc.) and some additional common species for comparison. The latter included the largest extant rodent species, capybara (*Hydrochoerus hydrochaeris*), a semi-aquatic lowland South American species that is common in zoos. Average maxillary incisor width ranged from 9.54 mm for capybara to 0.42 mm for house mouse (*Mus*

Figure 9.29 Rodent dry-bone gnawing on postcranial elements, exposing pale underlying bone. Top: long bone with gnawing on the margin and some in the flatter areas; bottom: close up of a rib with beginning gnawing, including visible striations where the parallel marks of the paired incisors are visible (arrows).

musculus), an invasive Palearctic species. Average mandibular incisor width ranged from 9.13 mm for capybara to 0.35 mm for house mouse. The largest native species was beaver (*Castor canadensis*), with an average maxillary incisor width of 6.29 mm and an average mandibular incisor width of 6.57 mm, followed by North American porcupine (3.53 mm maxillary, 3.95 mm mandibular). Both beaver and North American porcupine have widespread distributions throughout North America and have the potential to gnaw on bones in a variety of non-urban jurisdictions. The remaining species were all below 2.00 mm in average size for maxillary and mandibular incisors, and the majority were below 1.00 mm. Importantly, all species currently inhabiting Massachusetts, except for beaver, overlapped in incisor size range with other species. Smaller rodents may be indistinguishable from each other in their bone gnawing damage from dimensions alone. Eastern gray squirrel is common in this environment, includes urban areas in its range, and is a known avid bone gnawer (Pokines et al. 2016; Synstelien 2015) that can reduce bones to only portions of their former size through repeated gnawing (Figure 9.31). Its bone gnawing behavior, however, is relatively well-known, and additional research is needed for the many species that overlap it in incisor size.

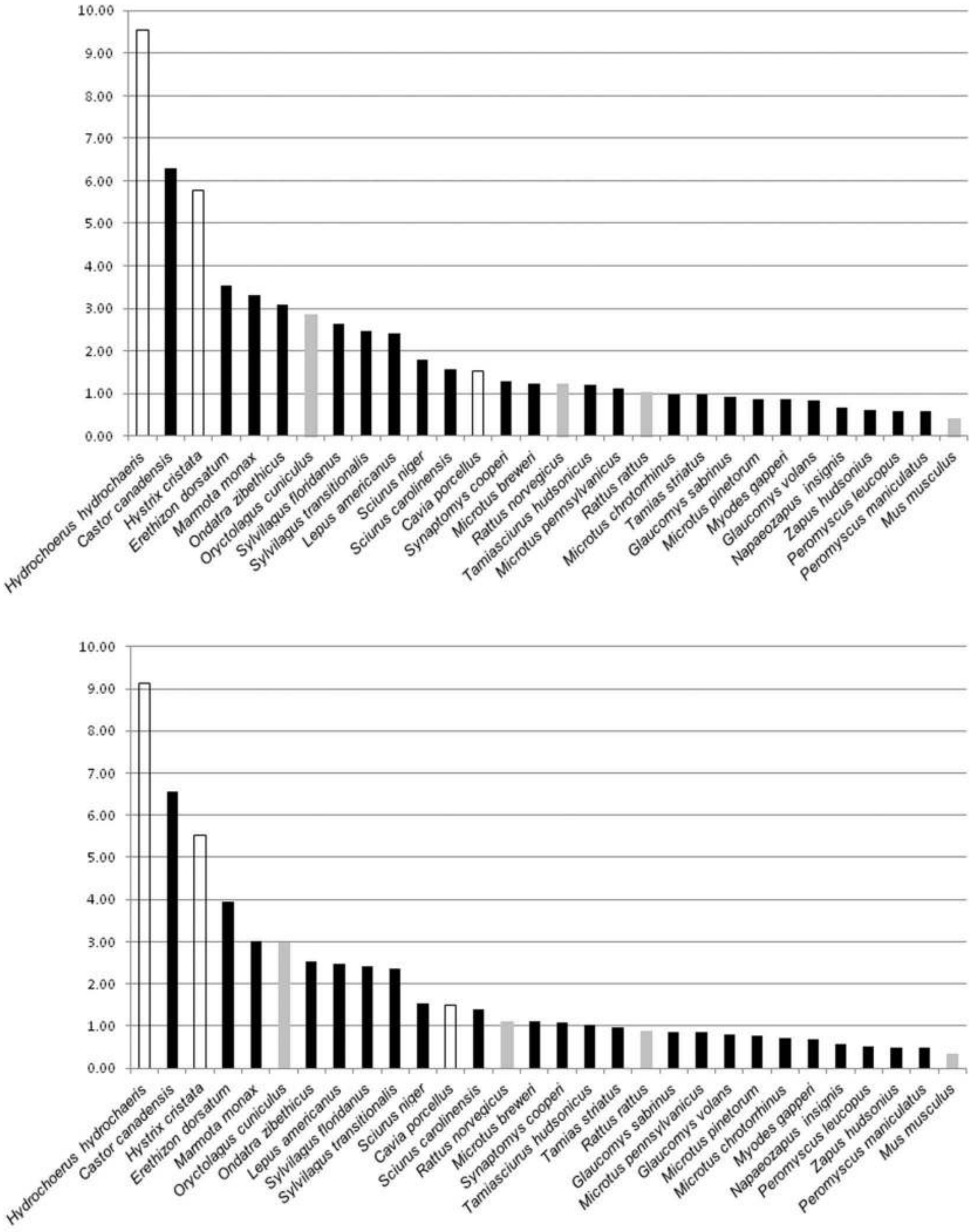

Figure 9.30 Rodent and lagomorph incisor average width (mm) of (top) maxillary and (bottom) mandibular incisors. Solid black bars: species native to Massachusetts, USA; solid gray bars: species introduced to that area; white bars: other common species for comparison. The species on the left, capybara (*Hydrochoerus hydrochaeris*), is the largest extant rodent species; the one on the right, house mouse (*Mus musculus*), has been introduced throughout the world. Many species overlap in size, making their gnawing marks likely indistinguishable. (From Pokines et al. 2017:56; used with permission, John Wiley and Sons.)

Figure 9.31 Dry, unfused white-tailed deer (*Odocoileus virginianus*) metacarpal wired to a tree and gnawed on by Eastern gray squirrel (*Sciurus carolinensis*), photographed at one-month intervals for five months from top (ungnawed, prior to placement) to bottom. Note the gradual destruction of the element from dry-bone gnawing. The scales are in cm.

Human Gnawing Characteristics

Occasionally in forensic contexts the question arises if humans have gnawed on a bone. This question is normally more relevant to analyses of cannibalism in the archaeological record, as in multiple Anasazi sites in the Southwest USA (Flinn et al. 1976; Graver et al. 2002; Lambert et al. 2000; Ogilvie et al. 2000; Turner 1993; Turner and Turner 1992, 1999; White 1992) or historical (Hardesty 1997) or modern (Read 2002) instances. As an omnivore, humans have posterior teeth adapted for grinding a variety of tough plant foods, with sharper anterior teeth also useful for shearing soft tissue; our species, however, has not evolved to be an efficient bone crusher. As with other mammals, a higher level of force can be applied closer to the fulcrum of the temporomandibular joint, but direct marks onto bone can also be inflicted with the anterior teeth.

Petrovic et al. (2019) experimentally induced adult human gnawing damage on a sample of thin bone segments cut from cleaned but uncooked bovine metatarsals, producing a sample of n = 2154 tooth marks. A variety of pits of different shapes (round, elliptical, drop-like, crescent, or other) were formed, along with some striations. No punctures or furrows were formed nor would be expected, given the experimental design. Stefanović et al. (2019) also were able to identify human child (i.e., primary teeth) marks on bone spoons from the Neolithic period in southeastern Europe through experimental comparison; marks on the spoons consisted of pits and striations. Romero et al. (2016) examined the results of experimental human gnawing upon sheep (*Ovis aries*) scapulae, radii, and first phalanges that still had some soft tissue and were either raw, roasted, or boiled. This produced a sample of n = 202 marks among 89 bones. The marks/damage were classified as pits (n = 45; 22.3%), punctures (n = 7; 3.5%), scores (n = 69; 34.1%), moderate or light furrows (n = 39; 19.3%), some category of jagged margins (n = 29; 14.4%), and crushing of cortical bone (n = 13; 6.4%).

Conclusions and Recommendations

Gnawing by terrestrial carnivores is one of the most damaging taphonomic processes that may happen to a bone, since many of these taxa have evolved behavioral, masticatory, and digestive mechanisms specifically to exploit bones as a nutritional resource. The commonness of this type of taphonomic alteration is indicated by the necessity for forensic research facilities decomposing humans or other large vertebrates to have these areas fenced in order to limit wholesale loss of remains and their dispersal and gnawing damage (Synstelien 2015). Normal scavenging feeding behavior includes a heavy component of bone dispersal away from the point of initial carcass/body deposition, further confounding efforts to analyze skeletal remains forensically. Similarly, gnawing attacks by rodents and other species further degrade bones in ways that may make them unidentifiable or unrecoverable. Through careful field recovery and analysis, the suites of characteristics (and potentially unique signatures) of these gnawing taxa possibly can be detected, even where these overlap on a set of remains. A number of recommendations to deal with this pervasive taphonomic occurrence are as follows:

1. Know what bone-altering taxa live in your area as a list of potential suspects (Table 9.8). These should be obtainable from regional mammal guides or researchers in other academic and museum departments. When in doubt, please note that many wildlife species are in fact reestablishing themselves in portions of their former North American ranges, including wolves (Thiel et al. 1998), coyotes, bears, moose, mountain lions, and smaller species, due to environmental protection, reduced hunting, the loss of smaller agricultural operations, and deliberate reintroductions. Please also note that some of these species, especially coyotes, have more urban ranges than normally assumed (Gehrt et al. 2009; Way 2007) and can be a factor in outdoor crime scene scavenging within city limits. Knowledge of scavenger behavior also may aid in the planning of surface recovery efforts (Young et al. 2016).

2. Obtain examples of gnawed bone from sources where the gnawing species is known. Long bones gnawed by domestic dogs should be easy to obtain and are valuable comparative material.
3. Examine other sources of taphonomic alterations that can produce marks mistakable for carnivore and rodent gnawing, including birds (Chapter 16) and, where applicable, large reptiles (Chapter 19). Degradation from acidic soils (Chapter 5) can mimic tooth marks, so one should determine the pH of soils at investigation scenes. Gnawing effects are common on nonhuman cases within an area and are an additional valuable source for comparative material (Pokines 2016).
4. Taphonomic research of this nature lends itself well to M.S.- and Ph.D.-level projects and is an underexplored area of investigation within forensic anthropology and related fields. Numerous taxa have been underexplored and could be pursued in conjunction with wildlife biologists.

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References

Alexander, A. J. (1956) Bone carrying by a porcupine. *South African Journal of Science* 52:257–258.

Andrés, M., A. O. Gidna, J. Yravedra, and M. Domínguez-Rodrigo (2012) A study of dimensional differences of tooth marks (pits and scores) on bones modified by small and large carnivores. *Archaeological and Anthropological Sciences* 4(3):209–219.

Arilla, M., J. Rosell, and R. Blasco (2019) Contributing to characterise wild predator behaviour: Consumption pattern, spatial distribution and bone damage on ungulate carcasses consumed by red fox (*Vulpes vulpes*). *Archaeological and Anthropological Sciences* 11(5):2271–2291.

Arilla, M., J. Rosell, and R. Blasco (2020) A neo-taphonomic approach to human campsites modified by carnivores. *(Nature) Scientific Reports* 10:6659. DOI: 10.1038/s41598-020-63431-8.

Arilla, M., J. Rosell, R. Blasco, M. Domínguez-Rodrigo, and T. R. Pickering (2014) The "bear" essentials: Actualistic research on *Ursus arctos arctos* in the Spanish Pyrenees and its implications for paleontology and archaeology. *PLoS ONE* 9(7):e102457. DOI: 10.1371/journal.pone.0102457.

Barthelmess, E. L. (2006) *Hystrix africaeaustralis*. *Mammalian Species* 788:1–7.

Bear, G. D. (1971) Seasonal trends in fat levels in pronghorns, *Antilocapra americana*, in Colorado. *Journal of Mammalogy* 53(3):583–589.

Beck, J., I. Ostericher, G. Sollish, and J. De León (2015) Animal scavenging and scattering and the implications for documenting the deaths of undocumented border crossers in the Sonoran Desert. *Journal of Forensic Sciences* 60(S1):S11–S20.

Becker, B., and C. A. Reed (1993) Studies of the bone detritus of the striped hyena (*Hyaena hyaena*) at a site in Egyptian Nubia, and the interaction of the bone breakage by striped hyenas. In *Skeletons in her Cupboard* ed. by A. Clason, S. Payne, and H. P. Uerpmann, pp. 157–182. Oxbow Monograph 34, Oxford.

Behrensmeyer, A. K. (1991) Terrestrial vertebrate accumulations. In *Taphonomy: Releasing the Data Locked in the Fossil Record* ed. by P. A. Allison and D. E. G. Briggs, pp. 291–335. Springer, Dordrecht.

Berryman, H. E. (2002) Disarticulation pattern and tooth mark artifacts associated with pig scavenging of human remains: A case study. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 487–495. CRC Press, Boca Raton, FL.

Betancourt, J. L., T. R. Van Devender, and P. S. Martin (eds.) (1990) *Packrat Middens: The Last 40,000 Years of Biotic Change*. University of Arizona Press, Tucson, AZ.

Betancourt, J., T. Van Devender, and M. Rose (1986) Comparison of plant macrofossils in woodrat (*Neotoma* sp.) and porcupine (*Erethizon dorsatum*) middens from the western United States. *Journal of Mammalogy* 67(2):266–273.

Binder, W. J., and B. Van Valkenburgh (2000) Development of bite strength and feeding behaviour in juvenile spotted hyenas (*Crocuta crocuta*). *Journal of Zoology (London)* 252:273–283.

Binford, L. R. (1981) *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Bischoff-Mattson, Z., and D. Mattson (2009) Effects of simulated mountain lion caching on decomposition of ungulate carcasses. *Western North American Naturalist* 69(3):343–350.

Blumenschine, R. J. (1986) Carcass consumption sequences and the archaeological distinction of scavenging and hunting. *Journal of Human Evolution* 15(8):639–659.

Blumenschine, R. J. (1988) An experimental model of the timing of hominid and carnivore influence on archaeological bone assemblages. *Journal of Archaeological Science* 15(5):483–502.

Boesch, C. (1991) The effects of leopard predation on grouping patterns in forest chimpanzee. *Behaviour* 117(3–4):220–242.

Bowyer, R. T. (1983) Osteophagia and antler breakage among Roosevelt Elk. *California Fish and Game* 69:84–88.

Brain, C. K. (1980) Some criteria for the recognition of bone-collecting agencies in African caves. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 107–130. University of Chicago Press, Chicago.

Brain, C. K. (1981) *The Hunters or the Hunted? An Introduction to African Cave Taphonomy*. University of Chicago Press, Chicago.

Bright, L. N. (2011) *Taphonomic Signatures of Animal Scavenging in Northern California: A Forensic Anthropological Analysis*. M.A. Thesis, California State University, Chico, CA.

Brink, J. W. (1997) Fat content in leg bones of *Bison bison*, and applications to archaeology. *Journal of Archaeological Science* 24(3):259–274.

Brothwell, D. R. (1976) Further evidence of bone chewing by ungulates: The sheep of North Ronaldsay, Orkney. *Journal of Archaeological Science* 3(2):179–182.

Cáceres, I., M. Esteban-Nadal, M. Bennàsar, and Y. Fernández-Jalvo (2011) Was it the deer or the fox? *Journal of Archaeological Science* 38(10):2767–2774.

Carlson, A. J. (1940) Eating of bone by the pregnant and lactating gray squirrel. *Science* 91(2372):573.

Carson, E. A., V. H. Stefan, and J. F. Powell (2000) Skeletal manifestations of bear scavenging. *Journal of Forensic Sciences* 45(3):515–526.

Cavallo, J. A., and R. J. Blumenschine (1989) Tree-stored leopard kills: Expanding the hominid scavenging niche. *Journal of Human Evolution* 18(4):393–399.

Christiansen, P., and S. Wroe (2007) Bite forces and evolutionary adaptations to feeding ecology in carnivores. *Ecology* 88(2):347–358.

Cohen, B. F., and J. M. Kibii (2015) Experimental study of bone modification by captive caracal (*Caracal caracal*); a model for fossil assemblage analysis. *Journal of Archaeological Science* 62:92–104.

Colard, T., Y. Delannoy, S. Naji, D. Gosset, K. Hartnett, and A. Bécart (2015) Specific patterns of canine scavenging in indoor settings. *Journal of Forensic Sciences* 60(2):495–500.

Corbett, J. (1944) *Man-Eaters of Kumaon*. Oxford University Press, Delhi, India.

Coventry, A. F. (1940) The eating of bone by squirrels. *Science* 92(2380):128.

Crader, D. C. (1983) Recent single-carcass bone scatters and the problem of "butchery" sites in the archaeological record. In *Animals and Archaeology: 1. Hunters and their Prey* ed. by J. Clutton-Brock and C. Grigson, pp. 107–141. British Archaeological Reports International Series 163, Oxford.

Delany-Rivera, C., T. W. Plummer, J. A. Hodgson, F. Forrest, F. Hertel, and J. S. Oliver (2009) Pits and pitfalls: Taxonomic variability and patterning in tooth mark dimensions. *Journal of Archaeological Science* 36(11):2597–2608.

Dixon, E. J. (1984) Context and environment in taphonomic analysis: Examples from Alaska's Porcupine River caves. *Quaternary Research* 22(2):201–215.

Domínguez-Rodrigo, M. (1999) Flesh availability and bone modifications in carcasses consumed by lions: Palaeoecological relevance in hominid foraging patterns. *Palaeogeography, Palaeoclimatology, Palaeoecology* 149:373–388.

Domínguez-Rodrigo, M., and A. Piqueras (2003) The use of tooth pits to identify carnivore taxa in tooth-marked archaeofaunas and their relevance to reconstruct hominid carcass processing behaviors. *Journal of Archaeological Science* 30(11):1385–1391.

Domínguez-Solera, S. D., and M. Domínguez-Rodrigo (2009) A taphonomic study of bone modification and of tooth-mark patterns on long limb bone portions by suids. *International Journal of Osteoarchaeology* 19:345–363.

Duthie, A. G., and J. D. Skinner (1986) Osteophagia in the Cape porcupine *Hystrix africaeaustralis*. *South African Journal of Zoology* 21(4):316–318.

Edmonds, H. M., and H. Glowacka (2020) The ontogeny of maximum bite force in humans. *Journal of Anatomy* 237(3):529–542.

Einarsen, A. S. (1956) Determination of some predator species by field signs. *Oregon State Monographs Studies in Zoology* 10:1–34.

Elgmork, K. (1982) Caching behavior of brown bears (*Ursus arctos*). *Journal of Mammalogy* 63(4):607–612.

Erickson, G. M., A. K. Lappin, T. Parker, and K. A. Vliet (2004) Comparison of bite performance between long-term captive and wild American alligators (*Alligator mississippiensis*). *Journal of Zoology (London)* 262:21–28.

Erickson, G. M., S. D. Van Kirk, J. Su, M. E. Levenston, W. E. Caler, and D. R. Carter (1996) Bite-force estimation for *Tyrannosaurus rex* from tooth-marked bones. *Nature* 382:706–708.

Esteban-Nadal, M, I. Cáceres, and P. Fosse (2010) Characterization of a current coprogenic sample originated by *Canis lupus* as a tool for identifying a taphonomic agent. *Journal of Archaeological Science* 37(12):2959–2970.

Faith, J. T., and A. K. Behrensmeyer (2006) Changing patterns of carnivore modification in a landscape bone assemblage, Amboseli Park, Kenya. *Journal of Archaeological Science* 33(12):1718–1733.

Fay, J. M., R. Carroll, J. C. Kerbis Peterhans, and D. Harris (1995) Leopard attack on and consumption of gorillas in the Central African Republic. *Journal of Human Evolution* 29(1):93–99.

Fisher, J. W. (1995) Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory* 2(1):7–68.

Flinn, L., C. G. Turner II, and A. Brew (1976) Additional evidence for cannibalism in the Southwest: The case of LA 4528. *American Antiquity* 41(3):308–318.

Fuller, T. K. (1989) Denning behavior of wolves in north-central Minnesota. *American Midland Naturalist* 121(1):181–184.

Galdikas, B. M. F. (1978) Orangutan death and scavenging by pigs. *Science* 200:68–70.

Galté, I., M. Ángeles Gallego, D. Giménez, V. Padilla, M. Subirana, C. Martín-Fumadó, and J. Medallo (2014) A body, a dog, and a fistful of scats. *Forensic Science International* 241:e1–e4.

Gambín, P., F. Ceacero, A. J. Garcia, T. Landete-Castillejos, and L. Gallego (2017) Patterns of antler consumption reveal osteophagia as a natural mineral resource in key periods for red deer (*Cervus elaphus*). *European Journal of Wildlife Research* 63(39):1–7. DOI: 10.1007/s10344-017-1095-4.

Garcia, S., A. Smith, C. Baigent, and M. Connor (2020) The scavenging patterns of feral cats on human remains in an outdoor setting. *Journal of Forensic Sciences* 65(3):948–952.

Gehrt, S. D., C. Anchor, and L. A. Whitehome (2009) Range and landscape use of coyotes in a metropolitan landscape: Conflict or coexistence? *Journal of Mammalogy* 90(5):1045–1057.

Gilmour, R., and M. Skinner (2012) Forensic scatology: Preliminary experimental study of the preparation and potential for identification of captive carnivore scat. *Journal of Forensic Sciences* 57(1):160–165.

Gobetz, K. E., and D. E. Hattin (2002) Rodent-gnawed carbonate rocks from Indiana. *Proceedings of the Indiana Academy of Science* 1:1–8.

Graver, S., K. D. Sobolik, and J. Whittaker (2002) Cannibalism or violent death alone? Human remains at a small Anasazi site. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 309–320. CRC Press, Boca Raton, FL.

Greenfield, H. J. (1988) Bone consumption by pigs in a contemporary Serbian village: Implications for the interpretation of prehistoric faunal assemblages. *Journal of Field Archaeology* 15(4):473–479.

Haglund W. D. (1991) *Applications of Taphonomic Models to Forensic Applications.* Ph.D. Dissertation, University of Washington, Seattle, WA.

Haglund, W. D. (1992) Contribution of rodents to postmortem artifacts of bone and soft tissue. *Journal of Forensic Sciences* 37(6):1459–1465.

Haglund, W. D. (1997a) Dogs and coyotes: Postmortem involvement with human remains. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 367–381. CRC Press, Boca Raton, FL.

Haglund, W. D. (1997b) Rodents and human remains. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 405–414. CRC Press, Boca Raton, FL.

Haglund, W. D., D. T. Reay, and D. R. Swindler (1988) Tooth mark artifacts and survival of bones in animal scavenged human skeletons. *Journal of Forensic Sciences* 33(4):985–997.

Haglund, W. D., D. T. Reay, and D. R. Swindler (1989) Canid scavenging/disarticulation sequence of human remains in the Pacific Northwest. *Journal of Forensic Sciences* 34(3):587–606.

Hardesty, D. L. (1997) *The Archaeology of the Donner Party.* University of Nevada Press, Reno, NV.

Harding, B. E., and B. C. Wolf (2006) Alligator attacks in southwest Florida. *Journal of Forensic Sciences* 51(3):674–677.

Harrison, D. J., and J. R. Gilbert (1985) Denning ecology and movements of coyotes in Maine during pup rearing. *Journal of Mammalogy* 66(4):712–719.

Hart, D. L. (2002) *Primates as Prey: Ecological, Morphological, and Behavioral Relationships between Primate Species and Their Predators.* Ph.D. Dissertation, Washington University, St. Louis, MO.

Hart, D. L., and R. W. Sussman (2008) *Man the Hunted: Primates, Predators, and Human Evolution* (rev. ed.). Westview Press, Cambridge, MA.

Haynes, G. (1980a) Evidence of carnivore gnawing on Pleistocene and Recent mammalian bones. *Paleobiology* 6(3):341–351.

Haynes, G. (1980b) Prey bones and predators: Potential ecologic information from analysis of bone sites. *Ossa* 7:75–97.

Haynes, G. (1981) *Bone Modifications and Skeletal Disturbances by Natural Agencies: Studies in North America.* Ph.D. Dissertation, Catholic University of America, Washington, DC.

Haynes, G. (1982) Utilization and skeletal disturbances of North American prey carcasses. *Arctic* 35(2):266–281.

Haynes, G. (1983) A guide to differentiating mammalian carnivore taxa responsible for gnaw damage to herbivore limb bones. *Paleobiology* 9(2):164–172.

Hidaka, O., M. Iwasaki, M. Saito, and T. Morimoto (1999) Influence of clenching intensity on bite force balance, occlusal contact area, and average bite pressure. *Journal of Dental Research* 78(7):1336–1344.

Hill, A. (1979) Disarticulation and scattering of mammal skeletons. *Paleobiology* 5(3):261–274.

Hill, A. (1980) Early postmortem damage to the remains of some contemporary East African mammals. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 131–152. University of Chicago Press, Chicago.

Hill, A. (1989) Bone modification by modern spotted hyenas. In *Bone Modification* ed. by R. Bonnichsen and M. H. Sorg, pp. 169–178. Center for the Study of the First Americans, Orono, ME.

Hill, A., and A. K. Behrensmeyer (1984) Disarticulation patterns of some modern East African mammals. *Paleobiology* 10(3):366–376.

Hillson, S. (1986) *Teeth*. Cambridge University Press, Cambridge.

Hockett, B. S. (1989) The concept of "carrying range": A method for determining the role played by woodrats in contribution bones to archeological sites. *Nevada Archaeologist* 7(1):28–35.

Hoffman, R., and C. Hays (1987) The eastern wood rat (*Neotoma floridana*) as a taphonomic factor in archaeological sites. *Journal of Archaeological Science* 14(3):325–337.

Horwitz, L., and P. Smith (1988) The effects of striped hyaena activity on human remains. *Journal of Archaeological Science* 15(5):471–481.

Hudson, J. (1993) The impacts of domestic dogs on bone in forager camps; or, the dog-gone bones. In *From Bones to Behavior: Ethnoarchaeological and Experimental Contributions to the Interpretation of Faunal Remains* ed. by J. Hudson, pp. 301–323. Center for Archaeological Investigations, Occasional Paper No. 21, Southern Illinois University, Carbondale, IL.

Hutson, J. M., C. C. Burke, and G. Haynes (2013) Osteophagia and bone modifications by giraffe and other large ungulates. *Journal of Archaeological Science* 40(12):4139–4149.

Kent, S. (1981) The dog: An archaeologist's best friend or worst enemy—the spatial distribution of faunal remains. *Journal of Field Archaeology* 8:367–372.

Kerbis Peterhans, J. C. (1990) *The Roles of Porcupines, Leopards, and Hyenas in Ungulate Carcass Dispersal: Implications for Paleoanthropology*. Ph.D. Dissertation, University of Chicago, Chicago.

Kerbis Peterhans, J. C., and L. Horwitz (1992) A bone assemblage from a striped hyaena den (*Hyaena hyaena*) in the Negev Desert, Israel. *Israel Journal of Zoology* 37(4):225–245.

Kerbis Peterhans, J. C., and T. Gnoske (2001) The science of 'man-eating' among lions *Panthera leo* with a reconstruction of the natural history of the Man-Eaters of Tsavo. *Journal of East African Natural History* 90(1):1–40.

Kerbis Peterhans, J., R. W. Wrangham, M. L. Carter, and M. D. Hauser (1993) A contribution to tropical rainforest taphonomy: Retrieval and documentation of chimpanzee remains from Kibale Forest, Uganda. *Journal of Human Evolution* 25(6):485–514.

Keyes, C. A., J. Myburgh, and D. Brits (2020) Scavenger activity in a peri-urban agricultural setting in the Highveld of South Africa. *International Journal of Legal Medicine*. DOI: 10.1007/s00414-020-02413-x.

Kierdorf, U. (1993) Fork formation and other signs of osteophagia on a long bone swallowed by a red deer stag (*Cervus elaphus*). *International Journal of Osteoarchaeology* 3:37–40.

Kierdorf, U. (1994) A further example of long-bone damage due to chewing by deer. *International Journal of Osteoarchaeology* 4:209–213.

King, K. A., W. D. Lord, H. R. Ketchum, and R. C. O'Brien (2016) Postmortem scavenging by the Virginia opossum (*Didelphis virginiana*): Impact on taphonomic assemblages and progression. *Forensic Science International* 266:576.e1–576.e6.

Kjorlien, Y. P. (2004) *Patterns in the Scattering of Remains due to Scavenger Activity*. M.A. Thesis, University of Alberta, Edmonton, Canada.

Kjorlien. Y. P., O. B. Beattie, and A. E. Peterson (2009) Scavenging activity can produce predictable patterns in surface skeletal remains scattering: Observations and comments from two experiments. *Forensic Science International* 188:103–106.

Klippel, W. E., and J. A. Synstelien (2007) Rodents as taphonomic agents: Bone gnawing by brown rats and gray squirrels. *Journal of Forensic Sciences* 52(4):765–773.

Kruuk, H. (1972) *The Spotted Hyaena*. University of Chicago Press, Chicago.

Kruuk, H. (2002) *Hunter and Hunted: Relationships Between Carnivores and People*. Cambridge University Press, Cambridge.

Kuyt, E. (1972) Food habits of wolves on barren-ground caribou range. *Canadian Wildlife Service, Report Series* 21:1–36.

Lambert, P. M., B. R. Billman, and B. L. Leonard (2000) Explaining variability in mutilated human bone assemblages from the American Southwest: A case study from the southern piedmont of Sleeping Ute Mountain, Colorado. *International Journal of Osteoarchaeology* 10:49–64.

Lindner, D. L., S. M. Marretta, G. J. Pijanowski, A. L. Johnson, and C. W. Smith (1995) Measurement of bite force in dogs: A pilot study. *Journal of Veterinary Dentistry* 12(2):49–52.

Lloveras, L., J. Nadal, and J. Maria Fullola (2020) Distinguishing the taphonomic signature of wolves from humans and other predators on small prey assemblages. *(Nature) Scientific Reports* 10:8030. DOI: 10.1038/s41598-020-64716-8.

Lochmiller, R. L., E. C. Hellgren, W. E. Grant, and L. W. Varner (1985) Bone marrow fat and kidney fat indices of condition in collared peccaries. *Journal of Mammalogy* 66(4):790–795.

Lupo, K. D. (1998) Experimentally derived extraction rates for marrow: Implications for body part exploitation strategies of Plio-Pleistocene hominid scavengers. *Journal of Archaeological Science* 25(7):657–675.

Lyman, R. L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

Lyver, P. O'B. (2000) Identifying mammalian predators from bite marks: A tool for focusing wildlife protection. *Mammal Review* 30(1):31–44.

Madrigal, T. C., and J. Z. Holt (2002) White-tailed deer meat and marrow return rates and their application to Eastern Woodlands archaeology. *American Antiquity* 67(4):745–759.

Malcolm, J. R. (1980) Food caching by African wild dog (*Lycaon pictus*). *Journal of Mammalogy* 61(4):743–744.

Marean, C. W., L. M. Spencer, R. J. Blumenschine, and R. J. Capaldo (1992) Captive hyena bone choice and destruction, the Schlepp effect, and Olduvai archaeofaunas. *Journal of Archaeological Science* 19(1):101–121.

McLoughlin, P. D., H. D. Cluff, and F. Messier (2002) Denning ecology of barren-ground grizzly bears in the central arctic. *Journal of Mammalogy* 83(1):188–198.

Mech, L. D. (1970) *The Wolf: The Ecology and Behavior of an Endangered Species*. Natural History Press, Garden City, New York.

Meckel, L. A., C. P. McDaneld, and D. J. Wescott (2018) White-tailed deer as a taphonomic agent: Photographic evidence of white-tailed deer gnawing on human bone. *Journal of Forensic Sciences* 63(1):292–294.

Merbs, C. F. (1997) Eskimo skeleton taphonomy with identification of possible polar bear victims. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 249–262. CRC Press, Boca Raton, FL.

Miller, G. J. (1969) A study of cuts, grooves, and other marks on recent and fossil bones. I. Animal tooth marks. *Tebiwa* 12:9–19.

Miller, G. J. (1975) A study of cuts, grooves, and other marks on recent and fossil bones. II. Weathering cracks, fractures, splinters, and other similar natural phenomena. In *Lithic Technology: Making and Using Stone Tools* ed. by E. H. Swanson, Jr., pp. 211–226. Aldine, Chicago.

Milner, G. R., and V. G. Smith (1989) Carnivore alteration of human bone from a late prehistoric site in Illinois. *American Journal of Physical Anthropology* 79:43–49.

Minetz, J. A. (2010) Rodent gnawing, wildfire, and cultural modification: Using forensic techniques to interpret historic artifacts from the Spencer Site. *Proceedings of the American Academy of Forensic Sciences* 16:181

Moraitis, K., and C. Spiliopoulou (2010) Forensic implications of carnivore scavenging on human remains recovered from outdoor locations in Greece. *Journal of Forensic and Legal Medicine* 17(6):298–303.

Moran, N. C., and T. P. O'Connor (1992) Bones that cats gnawed upon: A case study in bone modification. *Circaea* 9:27–30, 31–34.

Mori, E., S. Lovari, and G. Mazza (2018) The bone collector: Temporal patterns of bone-gnawing behaviour define osteophagia as a female prerogative in a large rodent. *Behavioral Ecology and Sociobiology* 72(6)1–8. DOI: 10.1007/s00265-018-2504-8.

Morin, E. (2007) Fat composition and Nunamiut decision-making: A new look at the marrow and bone grease indices. *Journal of Archaeological Science* 34(1):69–82.

Morton, R. J., and W. D. Lord (2006) Taphonomy of child-sized remains: A study of scattering and scavenging in Virginia, USA. *Journal of Forensic Sciences* 51(3):475–479.

Moss, K. E. (2012) *The Effects of Avian and Terrestrial Scavenger Activity on Human Remains and Decomposition in Southeast Texas During an 18 Month Study*. M.A. Thesis, University of Houston, Houston, TX.

Murad, T. A. (1997) The utilization of faunal evidence in the recovery of human remains. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 395–404. CRC Press, Boca Raton, FL.

Murmann, D. C., P. C. Brumit, B. A. Schrader, and D. R. Senn (2006) A comparison of animal jaws and bite mark patterns. *Journal of Forensic Sciences* 51(4):846–860.

O'Regan, H. J., K. Kuman, and R. J. Clarke (2011) The likely accumulators of bones: Five Cape porcupine den assemblages and the role of porcupines in the post-Member 6 infill at Sterkfontein, South Africa. *Journal of Taphonomy* 9(2):69–87.

Ogilvie, M. D., and C. E. Hilton (2000) Ritualized violence in the prehistoric American Southwest. *International Journal of Osteoarchaeology* 10:27–48.

Okarma, H. (1991) Marrow fat content, sex and age of red deer killed by wolves in winter in the Carpathian Mountains. *Ecography* 14(4):169–172.

Osborn, D. J., and I. Helmy (1980) *The Contemporary Land Mammals of Egypt (Including Sinai)*. Fieldiana: Zoology, New Series, No. 5, Chicago.

Patel, F. (1994) Artefact in forensic medicine: Postmortem rodent activity. *Journal of Forensic Sciences* 39(1):257–260.

Patterson, J. H. (1996) *The Man-Eating Lions of Tsavo*. Field Museum, Chicago.

Payne, S. B. (1983) Bones from cave sites: Who ate what? In *Animals and Archaeology: 1. Hunters and Their Prey* ed. by J. Clutton-Brock and C. Grigson, pp. 149–162. British Archaeological Reports International Series 163, Oxford.

Payne, S. B., and P. J. Munson (1985) Ruby and how many squirrels? The destruction of bones by dogs. In *Paleobiological Investigations: Research Design, Methods, and Data Analysis* ed. by N. R. J. Feller, D. D. Gilbertson, and N. G. A. Ralph, pp. 31–40. British Archaeological Reports International Series 266, Oxford.

Peterson, R. O. (1977) *Wolf Ecology and Prey Relationships on Isle Royale*. U.S. National Park Service Scientific Monograph Series No. 11, Washington, DC.

Petrovic, B., S. Stefanovic, S. Kojic, M. Porcic, J. Jevremov, and G. Stojanovic (2019) A pattern of metatarsal bovine bone surface alterations produced by human permanent teeth—An experimental approach. *Journal of Archaeological Science: Reports* 27:101961. DOI: 10.1016/j.jasrep.2019.101961.

Phillips, J. A. (1993) Bone consumption by cheetahs at undisturbed kills: Evidence for a lack of focal-palatine erosion. *Journal of Mammalogy* 74(2):487–492.

Pickering, T. R. (2001) Carnivore voiding: A taphonomic process with the potential for the deposition of forensic evidence. *Journal of Forensic Sciences* 46(2):406–411.

Pickering, T. R., and K. J. Carlson (2004) Baboon taphonomy and its relevance to the investigation of large felid involvement in human forensic cases. *Forensic Science International* 144:37–44.

Pierce, B. M., V. C. Bleich, C. L. B. Chetkiewcza, and D. Wehausen (1998) Timing of feeding bouts of mountain lions. *Journal of Mammalogy* 79(1):222–226.

Pobiner, B. L. (2007) *Hominin-Carnivore Interactions: Evidence from Modern Carnivore Bone Modification and Early Pleistocene Archaeofaunas (Koobi I, Kenya; Olduvai Gorge, Tanzania)*. Ph.D. Dissertation, Rutgers University, Newark, NJ.

Pobiner, B. L. (2008) Paleoecological information from predator tooth marks. *Journal of Taphonomy* 6(3–4):373–397.

Pobiner, B. L., and R. J. Blumenschine (2003) A taphonomic perspective on the Oldowan hominid encroachment on the carnivoran paleoguild. *Journal of Taphonomy* 1(2):115–141.

Pobiner, B. L., L. Dumouchel, and J. Parkinson (2020) A new semi-quantitative method for coding carnivore chewing damage with an application to modern African lion-damaged bones. *Palaios* 35(7):302–315.

Pokines, J. T. (2015) Taphonomic alterations by the rodent species woodland vole (*Microtus pinetorum*) upon human skeletal remains. *Forensic Science International* 257:e16–e19.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T., and C. Pollock (2018) The small scavenger guild of Massachusetts. *Forensic Anthropology* 1(1):52–67.

Pokines, J. T., and J. C. Kerbis Peterhans (2007) Spotted hyena (*Crocuta crocuta*) den use and taphonomy in the Masai Mara National Reserve, Kenya. *Journal of Archaeological Science* 34(11):1914–1931.

Pokines, J. T., S. A. Santana, J. D. Hellar, P. Bian, A. Downs, N. Wells, and M. D. Price (2016) The taphonomic effects of eastern gray squirrel (*Sciurus carolinensis*) gnawing upon bone. *Journal of Forensic Identification* 66(4):349–375.

Pokines, J. T., R. Sussman, M. Gough, C. Ralston, E. McLeod, K. Brun, A. Kearns, and T. L. Moore (2017) Taphonomic analysis of Rodentia and Lagomorpha bone gnawing based upon incisor size. *Journal of Forensic Sciences* 62(1):50–66.

Read, P. P. (2002) *Alive: The Story of the Andes Survivors*. Avon, New York.

Richardson, P. R. K. (1980) Carnivore damage to bones and its archeological implications. *Palaeontologia Africana* 23:109–125.

Ricketts, D. R. (2013) *Scavenging Effects and Scattering Patterns on Porcine Carcasses in Eastern Massachusetts*. M.S. Thesis, Boston University School of Medicine, Boston.

Romero, A. J., J. C. Díez, and P. Saladié (2016) Mammal bone surface alteration during human consumption: An experimental approach. *Journal of Archaeological Science: Reports* 8:82–89.

Roselle, J., R. Blasco, M. Arilla, and Y. Fernández-Jalvo (2019) Very human bears: Wild brown bear neo-taphonomic signature and its equifinality problems in archaeological contexts. *Quaternary International* 517:67–78.

Roze, U. (2009) *The North American Porcupine* (2nd ed.). Cornell University Press, Ithaca, NY.

Schmitt, D. N., and K. E. Juell (1994) Toward the identification of coyote scatological faunal accumulations in archaeological contexts. *Journal of Archaeological Science* 21(2):249–262.

Searfoss, G. (1995) *Skulls and Bones: A Guide to the Skeletal Structures and Behavior of North American Mammals*. Stackpole Books, Mechanicsburg, PA.

Simons, J. W. (1966) The presence of leopard and a study of the food debris in the leopard lairs of the Mount Suswa Caves, Kenya. *Bulletin, Cave Exploration Group of East Africa* 1:51–69.

Smith, C. F. (1948) A burrow of the pocket gopher (*Geomys bursarius*) in eastern Kansas. *Transactions of the Kansas Academy of Science* 51:313–315.

Sorg, M. H., M. C. Smith, W. D. Haglund, J. A. Wren, and A. Collar (2012) Taphonomic impacts of small and medium-sized scavengers in northern New England. *Proceedings of the American Academy of Forensic Sciences* 18:400.

Spies, M. J., D. A. Finaughty, and V. E. Gibbon (2018) Forensic taphonomy: Scavenger-induced scattering patterns in the temperate southwestern Cape, South Africa—A first look. *Forensic Science International* 290:29–35.

Steadman, D. W., and H. Worne (2007) Canine scavenging of human remains in an indoor setting. *Forensic Science International* 173(1):78–82.

Stefanović, S., B. Petrović, M. Porčić, K. Penezić, J. Pendić, V. Dimitrijević, I. Živaljević, S. Vuković, J. Jovanović, S. Kojić, A. Starović, and T. Blagojević (2019) Bone spoons for prehistoric babies: Detection of human teeth marks on the Neolithic artefacts from the site Grad-Starčevo (Serbia). *PLoS ONE* 14(12):e0225713. DOI: 10.1371/journal.pone.0225713.

Stiner, M. C. (1994) *Honor Among Thieves: A Zooarchaeological Study of Neandertal Ecology*. Princeton University Press, Princeton, NJ.

Sutcliffe, A. J. (1973) Similarity of bones and antlers gnawed by deer to human artefacts. *Nature* 246(5433):428–430.

Sutcliffe, A. J. (1977) Further notes on bones and antlers chewed by deer and other ungulates. *Deer* 4:73–82.

Synstelien, J. A. (2015) *Studies in Taphonomy: Bone and Soft Tissue Modifications by Postmortem Scavengers*. Ph.D. Dissertation, University of Tennessee, Knoxville, TN.

Tanner, J. B., E. R. Dumont, S. T. Sakai, B. L. Lundrigan, and K. E. Holekamp (2008) Of arcs and vaults: The biomechanics of bone-cracking in spotted hyenas (*Crocuta crocuta*). *Biological Journal of the Linnean Society* 95:246–255.

Tappen, M. (1995) Savanna ecology and natural bone deposition: Implications for early hominid site formation, hunting, and scavenging. *Current Anthropology* 36(2):223–260.

Thiel, R. P., S. Merrill, and L. D. Mech (1998) Tolerance by denning wolves, *Canis lupus*, to human disturbance. *Canadian Field-Naturalist* 122:340–342.

Treves, A., and L. Naughton-Treves (1999) Risk and opportunity for humans coexisting with large carnivores. *Journal of Human Evolution* 36(3):275–282.

Tsokos, M., J. Matschke, A. Gehl, E. Koops, and K. Puschel (1999) Skin and soft tissue artifacts due to postmortem damage caused by rodents. *Forensic Science International* 104:47–57.

Turner, C. G., II (1993) Cannibalism in Chaco Canyon: The charnel pit excavated in 1926 at Small House Ruin by Frank H. H. Roberts, Jr. *American Journal of Physical Anthropology* 91: 421–439.

Turner, C. G., II, and J. A. Turner (1992) The first claim for cannibalism in the Southwest: Walter Hough's 1901 discovery at Canyon Butte Ruin 3, northeastern Arizona. *American Antiquity* 57(4):661–682.

Turner, C. G., II, and J. A. Turner (1999) *Man Corn: Cannibalism and Violence in the Prehistoric American Southwest*. University of Utah Press, Salt Lake City, UT.

Ubelaker, D. H., and C. M. DeGaglia (2020) The impact of scavenging: Perspective from casework in forensic anthropology. *Forensic Sciences Research* 5(1):32–37.

Udoni, M. A. (2019) *Taphonomic Study of Black Bear* (Ursus americanus) *and Grizzly Bear* (U. arctos) *Tooth Marks on Bone*. M.S. Thesis, Boston University School of Medicine, Boston.

Udoni, M. A., J. T. Pokines, and T. L. Moore (2021) Experimental study of black bear (*Ursus americanus*) and grizzly bear (*U. arctos*) tooth marks and other gnawing damage on bone. *Forensic Anthropology*. DOI: 10.5744/fa.2020.0035.

Way, J. G. (2007) *Suburban Howls: Tracking the Eastern Coyote in Urban Massachusetts*. Dog Ear Publications, Indianapolis, IN.

White, T. D. (1992) *Prehistoric Cannibalism at Mancos 5MTUMR-2346*. Princeton University Press, Princeton, NJ.

Wilcox, J. T., and D. H. Van Vuren (2009) Wild pigs as predators in oak woodlands of California. *Journal of Mammalogy* 90(1):114–118.

Willey, P., and L. M. Snyder (1989) Canid modification of human remains: Implications for time-since-death estimations. *Journal of Forensic Sciences* 34(4):894–901.

Wilson, D. E., and D. M. Reeder (eds.) (2005) *Mammal Species of the World* (3rd ed.). The Johns Hopkins University, Baltimore, MD.

Woods, C. A. (1973) *Erethizon dorsatum*. *Mammalian Species* 29:1–6.

Wroe, S., C. McHenry and J. Thomason (2005) Bite club: Comparative bite force in big biting mammals and the prediction of predatory behavior in fossil taxa. *Proceedings of the Royal Society B: Biological Sciences* 272(1563):619–625.

Wroe, S., D. R. Huber, M. Lowry, C. McHenry, K. Moreno, P. Clausen, T. L. Ferrara, E. Cunningham, M. N. Dean, and A. P. Summers (2008) Three-dimensional computer analysis of white shark jaw mechanics: How hard can a great white bite? *Journal of Zoology (London)* 276:336–342.

Wyatt, J. R. (1971) Osteophagia in Masai giraffe. *African Journal of Ecology* 9:157.

Young, A., N. Márquez-Grant, R. Stillman, M. J. Smith, and A. H. Korstjens (2015a) An investigation of red fox (*Vulpes vulpes*) and Eurasian badger (*Meles meles*) scavenging, scattering, and removal of deer remains: Forensic implications and applications. *Journal of Forensic Sciences* 60(S1):S39–S55.

Young, A., R. Stillman, M. J. Smith, and A. H. Korstjens (2014) An experimental study of vertebrate scavenging behavior in a northwest European woodland context. *Journal of Forensic Sciences* 59(5):1333–1342.

Young, A., R. Stillman, M. J. Smith, and A. H. Korstjens (2015b) Scavenger species-typical alteration to bone: Using bite mark dimensions to identify scavengers. *Journal of Forensic Sciences* 60(6):1426–1435.

Young, A., R. Stillman, M. J. Smith, and A. H. Korstjens (2016) Applying knowledge of species-typical scavenging behavior to the search and recovery of mammalian skeletal remains. *Journal of Forensic Sciences* 61(2):458–456.

Deposition and Dispersal of Human Remains as a Result of Criminal Acts

10

Homo sapiens sapiens as a Taphonomic Agent[1]

DEREK CONGRAM
ARTHUR GILL GREEN
PEARL PEROUZ SEFERIAN

Contents

> The mopping-up operations practiced by the Black Squads have an evocative name: *el paseo* [“the stroll”]. They are carried out to such a characteristic pattern that one can talk of a method.
>
> **—Couffon, in Gibson (1973:73)**

> [T]he logistical aspect of the elimination of the corpses of victims have almost as important a place as the executions themselves.
>
> **—Kévorkian (2014:89)**

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Introduction

Scavenging behavior of human remains by wild and domestic animals has been widely researched (see Chapters 7, 9, 16, 18, and 19, this volume). Likewise, the natural decomposition processes of human remains have received much scientific attention in the form of forensic case reports and the increasing number of university-based research centers (e.g., Dabbs et al. 2016; Dautartas et al. 2018; Prieto et al. 2004). Despite these advances, the variable that arguably accounts for the most destructive effects upon human remains and that which most frustrates human remains recovery and identification is that of deliberate dispersal and disposal behavior by *Homo sapiens sapiens*. Considering this, there is remarkably very little forensic anthropological study of *H. sapiens sapiens* as a taphonomic agent. This situation is particularly surprising, given early definitions of anthropology as a scientific study of "man [sic] as an animal" (Oxford English Dictionary 2021).

This chapter examines what people do to the mortal remains of other people in different contexts of large-scale intergroup violence and the geographic or geometric taphonomic signature of such behavior. In essence, this chapter examines ecological behavior of humans relative to a sociopolitical niche that is quite unique to humans (e.g., killing conspecifics is, generally, very actively discouraged and severely punished when it occurs during peacetime, whereas it is actively encouraged during armed conflict [Bourke 2000]).

Distinct contexts and categories of body disposal are discussed, and the characteristics of body disposal sites are examined relative to different cultural, historical, and geographic variables. This chapter adopts a geographic approach by employing spatial analysis to examine trends in disposal behavior. We also use two case studies to exemplify the types of geographic influences on body disposal and postburial treatment and the taphonomic patterns that this produces. The aim of this chapter is to understand better this intraspecies predatory behavior, as a means of improving methods of body search and recovery, and ultimately the identification of both the victim and those responsible for body disposal. In an effort to move beyond anecdote and the linking of seeming cross-context coincidences, this chapter will demonstrate that predatory behavior by *H. sapiens sapiens* is often constrained by multiple measurable factors and results in predictable, limited disposal and dispersal patterns.

Study of *H. sapiens sapiens* as a Taphonomic Agent

In a forensic context, Haglund et al. (2001) warned against interpreting human behavior and processes, instructing that forensic anthropologists should document only facts and give defensible expert opinion (2001:67). What constitutes fact and defensible expert opinion, however, is debatable and dependent upon the onus of proof of a legal jurisdiction or the forum in which forensic anthropological evidence is presented. We argue that not only are forensic anthropologists and others potentially qualified to make certain interpretations about human behavior based on contextual, artifactual, spatial, relational, and taphonomic variables, but also that they should. Anthropological training and experience as the study of people generally enables one to do so with sufficient skill, depending on the context and circumstances of the case and question at hand. Competently analyzing and commenting on human behavior and processes may answer critical questions related to forensic death investigation, body identification, as well as the location and identification of those responsible. Going further, we emphasize that "anthropological" observations are not the exclusive domain of those with formal anthropological/archaeological training. In the animal kingdom, humans are perhaps uniquely self-obsessed, capable, and inclined to make observations about their own behavior. Though university training can introduce methods and help us refine our research skills, these abilities can come naturally to some who might lack discipline-specific training, or have in-depth knowledge of a case and its natural environment—as Fernandez Muñoz and Congram (2016) emphasized regarding observations about cultural objects.

There are sensible reasons why anthropologists generally do not incorporate the social and behavioral study of people into their forensic practice. One reason is that forensic anthropologists are almost exclusively physical anthropologists; their focus on the skeleton is largely biological, not sociocultural. When one considers the forensic anthropologist, however, as a bioarchaeologist (Skinner et al. 2003), the study of sociocultural behavior and its impact on the skeleton is much more apropos. Recently, parallel to a process of increasing certification with well-defined criteria about what constitutes forensic anthropological expertise (e.g., within the American Board of Forensic Anthropology, Latin American Forensic Anthropology Association, Forensic Anthropology Society of Europe, or the Royal Anthropological Institute), we have seen a broadening of who might be considered a forensic anthropologist as reflected by the name change of the Physical Anthropology section of the American Academy of Forensic Sciences to just "Anthropology," which recognizes contributions from archaeology and cultural anthropology. This shift has also been evidenced in oral and poster presentations in the Anthropology section at the American Academy of Forensic Sciences annual meetings.

A serious consideration for the lack of behavioral research by forensic anthropologists is the pressure for experts to employ tested methods and quantifiable results, particularly in light of certain legal judgments (e.g., *Daubert v. Merrell Dow Pharmaceuticals* 1993). Some forensic anthropological methods conform to evidentiary standards of the admissibility of scientific evidence; for example, calculating stature from long bones is generally straightforward, and point estimates are accompanied by a prediction interval. This seems to be what Haglund et al. (2001) were driving at when they warned against interpreting human behavior and advocated only the reporting of facts: avoid speculation about things of which you are uncertain and cannot be certain (e.g., provide a well-founded error range). Conclusions about human behavior are grounded in social sciences and can be highly variable, whereas conventional forensic anthropology is generally about biological science. Nevertheless, as forensic anthropologists have been employed in different contexts, or have found themselves being asked different questions by investigative agencies, they are beginning to incorporate conventional anthropological practice that studies social behavior and spatial contexts into the forensic realm (e.g., Baraybar 2008; Congram et al. 2017; Jasinski et al. 2021; Komar and Lathrop 2008; Moyssi et al. 2016; Skinner et al. 2009).

Patterns of Body Disposal During Armed Conflict

In the past 40 years, forensic anthropologists have increasingly been involved in large-scale investigations of genocide, crimes against humanity, war crimes, and humanitarian efforts that have required them to locate and excavate clandestine graves (e.g., Cordner and Tidball-Binz 2017; Steadman and Haglund 2005). These types of graves can include burials of battle casualties (e.g., Indra et al. 2020; Skinner 2007; Verna et al. 2020; Wessling and Loe 2011), executed prisoners of war, including combatants (e.g., Kamenetsky 1989; Szleszkowski et al. 2015), mass killings of civilians (e.g., Browning 1998; Flavel and Barker 2009), or a combination of these in a single burial, at a single burial site with multiple graves, and/or across a broader temporal and geographic area (e.g., Congram and Sterenberg 2009; Skinner et al. 2002). The work has been very task-oriented, resulting in institutionally confidential reports. So, despite this increasing involvement, there has been little published anthropological analysis of data derived from these investigations. At the same time, scientific research and investigative observations have noted spatial patterns of body disposal influenced by political territorial control and environmental variables (Congram et al. 2017). Below, we introduce several cases such as that of Sarajevo wherein the Bosnian Serb Army exhumed existing mass graves in order to move bodies to secondary graves in more clandestine locations in forests or where graves could be obscured by agricultural soil disturbances (ICTY 2003; Jugo and Wastell 2015).

Diverse Sources, Distinct Challenges

The lack of information and analysis is also true for victims buried in mass graves from the world wars, despite the atrocious numbers of victims and the relatively long time passed since both the events and the subsequent Nuremberg trials of political and military leaders (a laudable exception being a recent special issue of *Forensic Science International*) (Márquez-Grant and Errickson 2021). The most obvious reason for this lack is that millions of victims of the Nazi extermination policy were not buried at all but cremated at internment camps (Ball 1999:41). Internment camp exterminations, however, were preceded by systematic mass shootings and burial by the Nazis, particularly in Eastern Europe and Russia. Information available for cursory analysis is mostly via witness testimony and documentary evidence (e.g., Browning 1998; Desbois 2008; Rhodes 2002), rather than from systematic grave excavations. Another reason for a lack of grave excavations in Europe may relate to continuing political sensitivity about the crimes. In Estonia, for example, the killing of "Gypsies" (i.e., Roma) was so pervasive that almost no group members survived to call for social or legal justice, and although the Germans orchestrated and implemented the killings, many Estonians of the time considered the "Gypsies" an annoyance and had wished for their elimination (although not necessarily their extermination) (Weiss-Wendt 2003).

Accounts of WWII-era grave excavations do exist, but many lack detail, are anecdotal, are limited to single burials, or the identification of victims and/or offenders are uncertain (e.g., Gojanović and Sutlović 2007; Mark 2010 on Romania; Palo et al. 2007; Raszeja and Chróścielewski 1994; Susa 2007 on Hungary). Despite an entire text being dedicated to the "archaeology of twentieth century conflict" and much attention given to WWII (Schofield et al. 2002), there is no mention of grave excavations from the war. Immediately following World War II, Mant (1987) led the opening of several mass burials for the purpose of collecting evidence for the Nuremberg trials, but observations made by Mant related mostly to taphonomic factors related to human decomposition, which was the topic of his medical degree thesis.

Eastern European concentration camps and Natzweiler in France were destroyed as Nazis fled Allied advances, in an attempt to hide evidence of the camps' existence (Beech 2002:201; Rees 2005:194). Forests were planted over the destroyed sites at Belzec, Treblinka, and Sobibor (Rhodes 2002:265). This is an important observation for those investigating missing persons: the sociopolitical sensitivity of killings may lead offenders to destroy, or disguise—so far as is possible—traces of the killings and body disposal sites.

Other reasons for a dearth of grave excavations include a lack of political desire to confront the past (e.g., Beech 2002:206; Walston 1997), Jewish religious prohibitions related to the “disturbance” of the dead (Rosenblatt 2015:125–152; Sturdy-Colls 2015:87–111; Wolentarska-Ochman 2006), lack or unreliability of witnesses, financial constraints (Maver 2004), and fear of reviving interethnic rivalry (Bax 1997; Kovras 2012; Rosenblatt 2015). Access to archives and documents, particularly those in the custody of the former USSR, was severely restricted until recently, although Desbois (2008:173, chapter 5, footnote 4) reported that postwar Soviet commissions created 16 million pages of documentation of Nazi crimes and often opened victim mass burials to verify the testimonies of the killings. A copy of these archives exists in the US Holocaust Memorial Museum in Washington, DC. Lack of access to information in the custody of the Russians is also a factor in the case of the Spanish Civil War, where archives from toward the end of the war were confiscated by the Soviets, who heavily supported the Republicans and prevented documents from public review until recently (Petrou 2005). On the other side of the conflict in Spain, the postwar dictatorship ensured that the Nationalist narrative of the war dominated, extolling a single offender (the Republicans), grossly exaggerating the number of Nationalist victims, and seriously understating their own culpability and the scale of Nationalist killings (Badcock 2005:69; Espinosa 2006:95–97; Graham 2005:133; Richards 2007). To maintain this narrative, access to Nationalist archives from the war and postwar repression that were not destroyed has been severely restricted (Espinosa 2006:5, 6, 318; Reig Tapia 1979; Ruíz 2009). Work by civil society in Spain since the year 2000, however, has brought other deaths to light, resulting in over 9000 exhumations (Etxeberría and Solé 2019; Ferrándiz and Silva Barrera 2016).

Despite all of the earlier explanations for a lack of comparable and analyzable data, there are a couple of unusual and interesting examples of mass grave excavations and exhumations led by the Nazi Germans during WWII. Probably the earliest controlled excavation of mass burials for medico-legal (and political) purposes was conducted by representatives of the Nazi Third Reich in 1942 and 1943 in German-occupied Poland and Ukraine. The excavations were at times conducted with international medicolegal experts and a representative of the Polish Red Cross as witnesses with the purpose of documenting mass executions committed by the Soviets only a few years prior (Kamenetsky 1989), and these are discussed in greater detail below.

In 1990 and 1991, mass graves were excavated as part of an investigation of Nazi crimes. These investigations were conducted by a joint Australian and Soviet team, employing Australian archaeologist Richard Wright to excavate WWII mass burials of Jewish victims at Serniki and Ustinovka, Ukraine. Evidence indicated that the victims had been murdered by the Nazis one year *before* the Nazi-led exhumations and their accusations of Soviet mass murder described earlier (Wright et al. 2005).

Site Selection Decision Factors

Patterns of victim body disposal likely exist in the context of armed conflict for three reasons: resources are generally limited, especially personnel and equipment; geographic constraining factors—particularly when the number of victims is in the thousands; and sociopolitical factors that influence whether killings and victims will be hidden or, less commonly, made public as an example to others. The extent to which body disposal patterns are consistent within and between contexts, however, is unknown. A systematic study comparing these events has not previously been published, but an analysis of relevant literature and observations by the authors suggests that logistics and the sensitivity of the killings (based in part on victim identity and the sociopolitical context) are the two primary factors that determine where and how killers dispose of victim bodies. The presence of labor to dig graves, locations to which the typically large groups of victims can be transported, and the availability of preexisting features for burial are all logistical considerations that appear to factor strongly in killers' decisions about where and how to dispose of victim bodies. The use of natural features such as cliffs, caves, rivers, and lakes to dispose of large amounts of bodies in the Armenian genocide (see "Case Study: Body Disposal During the Armenian Genocide" section, below) points to such logic. The logistics of mass body disposal also include the necessity of detaining victim groups; preparing or locating suitable body disposal sites; moving victims to detention, execution, and disposal sites; and arranging personnel to gather, guard, transport, and then kill. All of these things generally must occur within a limited geographic area that has constraints including but not limited to transportation infrastructure, topography (e.g., mountainous areas), geology (e.g., exposed bedrock preventing burial), bodies of water, and secure territory under the control of those conducting the killings. Kalyvas (2006:38) noted that "war entails more constraints and less consent… [and] the stakes are incomparably higher for everyone involved", and so killers' options with respect to body disposal are generally quite limited unless a significant proportion of the power of a state or army is available and applied toward the task (e.g., Nazi Germany). In other cases where states have committed their resources toward large-scale noncombatant murder and body disposal, the worst crimes appear to have occurred while war was either pending or just ending, thus enabling the mobilization of lethal weapons and labor for noncombat activity (e.g., the Soviet Union in 1937 and 1938 or Iraq under the Baath Party and their purge of the Kurdish population following the Iran-Iraq war).

Given the horrendous scale of the killings and the typically limited resources of the killers during active armed conflict, logistics play a major role in how and where victims are disposed. Rhodes (2002:xi–xii) commented on the role of the Nazi *Einsatzgruppen* (paramilitary death squads) who were tasked with eliminating Jews and other "enemies" in the rearguard in Eastern Europe and Russia: "their assignment was to murder Jews, not indirectly by herding them into gas chambers but directly, by *shooting them into antitank ditches, natural ravines or pits freshly dug by Russian prisoners of war…* the *Einsatzgruppen* massacres preceded the invention of the death camps and significantly influenced their development" [emphasis added].

An example of sociopolitical sensitivity during WWII is given by Browning (1998:13), who cites an order by Nazi Colonel Max Montua regarding executions of Jews in Poland: "The shootings are to take place away from cities, villages, and thoroughfares. The graves are to be leveled in such a way no pilgrimage site can arise. I forbid photographing and the permitting of spectators at the executions. Executions and grave sites are not to be made known." In many instances, selecting burial sites at or just outside of prisons or military installations served the dual purposes of ensuring against investigation of the killings as well as making victim transport to burial sites logistically simple, as these places are where the victims were often detained and killed. There are many instances of victims being buried at military facilities in various conflicts, including the Orchard site in Vinnytsia (see "Mass Burial in Graves" section, below), in Iraq (Human Rights Watch 2004), Bosnia (Berman 2003), Kosovo (Jennings 2009), Guatemala (AP 2003), and Serbia (ICMP 2004), to name only a few.

Body Disposal Methods

A disturbingly common question that forensic anthropologists tend to hear is "So, what is the best way to get rid of a body?" In fact, we know only those methods that failed in some manner. It stands to reason, following the line of thought of the questioner, that the "best" is that which goes undiscovered and evades detection. The most common method, however, appears to be burial. Nevertheless, other body disposal methods are often employed.

Surface Deposition and the Use of Preexisting Features

In some instances, the twin parameters of discretion and logistics work against each other. The desire to kill in an area of heavy cover (e.g., forest) can preclude one's ability to bury at the same location because of an abundance of tree roots and inaccessibility of the location to heavy machinery to dig large graves. It is unknown if this was the reason that victims were not buried, for example, in the initial killings in July 1942 by Nazi paramilitary (German Reserve Police Battalion 101) in occupied Poland at Józefów. Burial of subsequent mass killing victims by the same unit, however, suggests that this is so, as with the September 1942 mass killing of Jews from Serokomla at an open quarry and waste dump in Poland (Table 10.1).

One of the clearer examples of the importance of logistics is the massacre of almost 34,000 Jewish men, women, and children by a few hundred members of *Einsatzgruppe* C in September 1941. When the Germans defeated the Soviets at Kiev, they took the Jewish population to a ravine called Babi Yar on the western edge of Kiev, where they were shot. The task of so few soldiers killing and burying so many was so great that a use of a preexisting feature as a grave was necessary. With a summer of experience in mass killing behind them, the *Einsatzgruppen* "had become expert at picking killing sites; Babi Yar could have swallowed the entire population of Kiev" (Rhodes 2002:173). At the end of each day of killings, workers shoveled sand down the ravine walls to cover the bodies. After three full days of killings, the walls of the ravine were dynamited, burying the victims (Rhodes 2002:178).

This pattern of using preexisting features as execution and burial sites is very common—in WWII (e.g., Desbois 2008:209), the Spanish Civil War (e.g., Herrero Balsa and Hernández García 1982; Silva and Macías 2003), the Balkan wars of the 1990s (Human Rights Watch 1997; Manning 2000; Simmons 2002; Wright 2010), Colombia (El Tiempo 2007; Gómez-López and Patiño Umaña 2007), Armenia (Seferian 2015), and others—and typically indicates not only that a massacre was intended, but that it was planned in advance (Browning 1998; Rhodes 2002).

Not in all instances where preexisting features were used were the victims subsequently buried. There are many examples of bodies simply being thrown in wells, including in Kosovo (e.g., Hirz 1999; Lecomte and Vorhauer 1999; OSCE 1999) and Guatemala (e.g., Flavel and Barker 2009). A further category that lies somewhere between "surface deposit" and "burial" includes the disposal of bodies into rivers as in the Spanish Civil War (Herrero Balsa and Hernández García 1982; Zavala 2006), Armenian Genocide (Seferian 2015), and Columbia (El Tiempo 2007). Bodies have also been disposed out of airplanes over the ocean as during Argentina's "Dirty War" (Tremlett 2005).

Table 10.1 WWII Mass Burial Characteristics

Site	Site Type	No. of Graves	Victims	Offender	Victims	Circumstances of Death	Killed at Burial Loc.?	Distance from Populated Area	Site Disguised Post-Killing?	Grave Features	Additional Observations
Vinnytsia 1, Ukraine	Orchard, NKVD shooting range	34	5644 (53 females)	Soviets, NKVD	Civilians; Mostly Ukrainians, also Russians, Jews, Gypsies, Poles	Mostly execution at back of neck/head by small caliber pistol, 1938–1939	No	1.8 km	Yes (fenced, guarded)	~2–3.8 m in depth; often a layer of clothing and possessions over bodies; lime over bodies	Bodies examined in situ 1943; winter clothing suggests killings in winter; site 1: bodies laid out neatly unlike sites 2 and 3; hands, elbows or upper arms of men bound behind back with twine
Vinnytsia 2, Ukraine	Former Orthodox cemetery	40 (+ 2 empty)	2405 (85 females)				No	600 m			
Vinnytsia 3, Ukraine	Park, outside NKVD prison	13 found, poss. more graves	>2583 (31 females)				No	North of Vinnytsia 2			
Katyn, Russia	Forest by NKVD "rest house"	8	4599	Soviets, NKVD	Polish troops, officers, and civilians (POWs)	Feb–May 1940, mostly executed at back of neck/head by 7.65 mm caliber pistol at NKVD prison in Smolensk and abattoir; 3.5%–4.7% had blunt force skull trauma	Some	Smolensk to Katyn Forest ca. 15 km; 6.5 km from Gnezdovo train stn.; 1.2 km from main road	Pine, fir, or birch trees planted over graves (reports differ)	1.8–3.4 m deep; bodies stacked neatly in 12 layers; graves prepared in advance	Investigated by Nazis in 1943, vic. hands generally tied behind backs, blunt force and stab trauma to some; sand over bodies helped to mummify; killers given vodka
Ulla, Belarus	Field	>26	800–1000, exhumations suspended before complete	Nazis	Mostly Polish, ~200 Jews, a few Lithuanians, mostly middle-upper class	27 June 1941; prisoners were being marched when Soviet base came under German air attack. Prisoners were told to take cover in a field and then shot.	Yes	Within 1 km of small town of Ulla, near Nikolayev			Buried by inhabitants of Nikolayev under order of the NKVD
Serniki, Ukraine		1	553 Jews: 407 female; 98 male; 48 undetermined according to cranial features	Nazis	Jewish civilians	September 1942; 74% gunshot to head; 1.8% depressed skull trauma; 24% undetermined cause of death; many appear shot by 9 mm handguns; apparently two groups killed differently, buried together	Yes	3 km		Grave prepared in advance	Bodies examined *in situ* and not removed from grave; some bodies clothed, others not and clothing found in overburden

(Continued)

Table 10.1 ***(Continued)*** **WWII Mass Burial Characteristics**

Site	Site Type	No. of Graves	Victims	Offender	Victims	Circumstances of Death	Killed at Burial Loc.?	Distance from Populated Area	Site Disguised Post-Killing?	Grave Features	Additional Observations
Ustinovka, Ukraine		1	19 children, 100–150 adults	Nazis	Jewish civilians	1942	Yes			Two layers of bodies: children; 20 cm soil; adults	Ramped grave
Bialystok, Poland	Forested area outside the city		>3000	German Reserve Police Batts.	Local Jewish civilians		Yes				
Józefów, Poland	Forest	0	1500	German Reserve Police Batt. 101	Local Jewish civilians	13 July 1942	Yes	Several km from the city		Victims left on surface	Batt. physician instructed shooters on how to shoot to kill: aiming with bayonet at back of neck; bodies left lying on surface in forest, not buried
Lomazy, Poland	Forest	1	1700	Hiwis, Trawnikis* German Reserve Police Batt. 101, 2nd Co.	Local Jewish civilians	17 August 1942		1 km from city		Local Jews were forced to dig the grave, ramped grave	Victims were forced to undress; shooters were drunk
Serokomla, Poland	Gravel pits and waste dump	0	200–300	German Reserve Police Batt. 101, 1st and 3rd Co.		September 1942		< 1km from city		Victims not buried	
Miedzyrec, Poland	Cemetery		Local Jewish civilians; ~150 mostly women and children			3 October 1942. Victims did not fit on a deportation train. Were shot in groups of 20, men first, then women and children					Shooters were given vodka prior to shootings

Understanding these methods of body disposal is rather complicated. The action of throwing a murdered victim into a body of water generally requires little effort. The possibility of victim's body discovery, however, can be great, as at certain postmortem stages, bodies can float and wash ashore (Chapters 6 and 7). Body disposal in wells almost guarantees discovery in the cases where wells are common public places. In the case of victims thrown out of airplanes off the coast of Argentina, however, the disposal method over water appears to have been very deliberate, with weights attached to victims' feet to prevent their floating to the surface, and victims thrown out at great heights (Tremlett 2005).

Mass Burial in Graves

Surprisingly good evidence of mass killings and burials in Poland, Ukraine, and Belarus is available from a series of Nazi-led exhumations in June-September, 1943. The Germans, blaming the Soviets for the deaths, widely distributed details about the events as part of a propaganda campaign designed to mobilize public opinion in favor of the Nazis and against the Soviets, the territory having been under the control of both groups at various times before and throughout the war. Dozens of mass graves were excavated, and the victims were examined by German scientists. These excavations were monitored by members of an international investigations commission from 13 European countries. In Ulla, Belarus, it is interesting to note that exhumations were stopped prematurely when the Nazis discovered that the victims were Poles and not Latvians (as they had previously suspected). The Nazis had been trying to gain political and military support from the Latvians against the Russians (Kamenetsky 1989:33–34). Kamenetsky (1989) further claimed that these three sites in Eastern Europe are the best-documented of Soviet secret police force (People's Commissariat of Internal Affairs or NKVD) executions and mass graves. Despite the age of the documentation (in and around 1943) and the overtly political motivation of the exhumations, they represent among the best publicly available data on mass grave excavations to date, having only been surpassed by recent efforts in Spain.

Graves at Vinnytsia, Ukraine, are reported to have been between 2 and 3.8 m deep (Kamenetsky 1989:97–98). There was often a layer of clothing and sometimes other personal artifacts found above the level of the bodies, suggesting that some of the victims had been stripped—perhaps to rob them of valuables—before being killed. In total, 9432 bodies were exhumed from 86 to 87 mass graves (numbers differ according to various reports), with all the victims being civilians so far as could be determined from clothing. The German government report reproduced by Kamenetsky (1989:91–141) also makes observations about the use of lime and other taphonomic aspects of the victims and graves, including the formation of adipocere, which was used to estimate a minimum postmortem interval (PMI). That researcher further noted the important fact that victims exhumed from graves at Vinnytsia were shot at close range in the back of the head and neck and had their hands bound behind their backs, with rope tied by knots the same as those found at Katyn, Poland (Kamenetsky 1989:34). Some victims (3.5%–4.7% ranging across three sites) had crushing skull trauma, probably from being hit with rifle butts (Kamenetsky 1989:116–117). The German Forensic Medical Report noted, however, that the method of binding differed somewhat in certain cases from Katyn, where victims had been tied at the elbows. The vast majority of the victims exhumed in these cases were male, all but one of whom were bound. Women were not tied.

Allen (2010) (see also FitzGibbon 1971, 1975; Raszeja and Chróścielewski 1994) related that over 4000 bodies were exhumed from graves at Katyn. Seven mass graves found in

March 1943 held the bodies of Polish Army officers and other civilians (men and women), 2730 of whom were identified via documentation found with the individual bodies (FitzGibbon 1971:146). The largest grave was L-shaped and measured 26 m long and 8 m at its widest point. In it were 12 layers of approximately 2800 bodies, with some neatly stacked and with heads and feet alternating. The vast majority were executed by a gunshot to the back of the neck at the base of the skull, using 7.65 mm pistol ammunition. The graves were between 1.8 and 3.4 m deep (Allen 2010:110–112). Evidence of broken jaws and stab wounds, presumably suffered prior to being shot, were also noted. FitzGibbon (1971:140) went on to quote the police report: "From the position of the bodies it may be assumed that the majority were murdered outside the graves. The bodies were in a complete tangle, except in graves Nos. 1, 2 and 4, where some of them lay side by side or on the top of each other… Very many of the dead had their hands tied behind their back." According to the reports discussed by Kamenetsky (1989), a general lack of shell casings at the sites led the investigators to the conclusion, supported by local witness testimony, that the executions had occurred at prisons. Documents showed that the Ukrainian victims were killed in a garage that had a special sewer to drain away the blood. Executions at one location and mass burial at another are therefore consistent with the testimony given about the killings at Katyn. This and other features of the burials demonstrate a common *modus operandi* by Soviet forces, which unsurprisingly suggests a coordinated effort.

Of primary relevance to this research is the location of these mass burials, as well as the fact that the burial site was often not the site of the killings. Kamenetsky (1989) reported that the Soviets wanted to give the survivor population the impression that the prisoners had actually been sent to corrective labor camps. The killings were apparently conducted with much secrecy, although that thousands could be executed in such a short time to the complete ignorance of the local populace is dubious. In Vinnytsia there were three burial sites, each with multiple mass graves. One site was in an orchard approximately 2 km from the city center, which at the time of the killings was being used as a shooting range by the NKVD. A second site was at the edge of a former (then in disuse) Orthodox Cemetery about 600 m from the city center. A third site bordered an NKVD prison, slightly further than the second site from the city center.

The work conducted in 1990 and 1991 by the Australians and Soviets is subject to publication limitations for judicial reasons, but different accounts about the two Ukrainian sites investigated do exist from which we know the following.

At Ustinovka, there were two layers to the mass grave. The uppermost layer held 19 children, beneath which was about 20 cm of fill, then 100–150 adults (ABC TV Science 2000; Wright 1995). The stratigraphic sequence of bodies indicates that adults were killed first, then the children. That soil was placed on top of the bodies of the adults suggests that the children were not present when the adults were killed. This layering of bodies—representing the shooting of individual groups of victims, which were covered by soil prior to the delivery and execution of a subsequent group of victims—is a method that also was sometimes employed by the Nazis in Poland (Browning 1998).

The grave had a ramp, which according to a witness was used by victims to walk into the grave before being shot. Browning (1998) reported the same feature in some graves created by the Nazis in Poland. The position of the bodies contrasted at the two different ends of the Serniki grave: at the end farthest from the ramp, victims were found lying parallel to one another, face down, and in rows where they had been shot in the backs of their heads (Wright 1995; Wright et al. 2005:144). A smaller number of bodies were lying in the grave in a much more disorganized fashion at the base of the ramp, consistent with a witness statement that most victims had been lying down when shot, while others who arrived in a later group were beaten with clubs and thrown into the grave (Wright 2010). Bevan (1994:58–59) reported 410 of 553 (74%) victims with gunshot trauma to the head, 10 (1.8%) with depressed skull fractures, and 133 (24%) with undetermined cause of death. It is important to note that full exhumations and autopsies were not performed on these bodies; only skulls were examined and in situ. Bevan (1994) also mentioned that many appeared to have been shot with German 9 mm (hand gun) ammunition. The two different body deposition types in the grave and the prevalence of cranial trauma at the base of the ramp indicate a diachronic change in the killings. This change is consistent with reports by Browning (1998) of Nazi killings in Poland, showing increasing killer impatience and sadism, fueled in part by alcohol, as killings progressed. A further change in victim treatment was observed by Wright (1995) at the grave at Ustinovka, where only some victims were wearing remaining pieces of clothing (parts having degraded over time), but clothing presumably from other, undressed victims had been found throughout the overburden, suggesting that it had been picked through and thrown in during the backfilling of the grave. Changes in victim treatment and killing at a single site complicate the search for commonalities among mass grave patterns but at the same time indicate patterns in human behavior when similar series of events are observed elsewhere. At both Ustinovka and Serniki, it was determined that the Nazis were responsible for the killings (Wright 1995). Bevan (1994:59) also noted that based on examinations of the skulls at Serniki, 407 of the bodies were estimated to be female, 98 male, and 48 undetermined. Possible explanations for this unusual demographic is that males were deported to work as slave labor for the Nazi war effort or that males were killed separately, both of which often occurred during Nazi occupation (Browning 1998).

Burning of Bodies

Burning of victim bodies is not uncommon in domestic and armed conflict contexts. Nevertheless, it is a costly method, since destruction of bodies is not easily accomplished by fire (Warren and Maples 1997; Chapter 14). Burning of bodies was a more elaborate means of disposal at the beginning of the Spanish Civil War (Reig Tapia 2006:529). This method was notoriously employed on the victims of the Badajoz massacre in 1936, where thousands of prisoners were machine-gunned in the city bullring. The killing and burning of bodies at a local cemetery were reported and photographed by several foreign journalists, creating international alarm over the mass executions (Espinosa 2006; Pons Prades 2006). Influential countries including the UK, the USA, and France were officially neutral during the Spanish Civil War, and to a degree, they limited or prohibited supplies from outside Spain reaching either party in the conflict. Recognizing that what was planned as a military coup was turning into a civil war and that resources such as fuel were in short supply, the Nationalists were keen to avoid negative publicity from massacres that might move other countries to support the Republicans. After Badajoz, the Nationalists seem to have turned to a different program of detention and smaller-scale but still systematic killings, followed by victim burial as the primary body disposal method.[2] Other sources record the burning of victim bodies early in the war in Bosnia (Berman 2003:278) and in Serbia of Kosovo Albanians (ICMP 2004).

Burning bodies as a means of disposal was not the first choice by the Nazis during WWII. Rees (2005:101–102) recounted prisoner testimony about how, prior to the completion of the crematorium at Auschwitz, bodies were buried by prisoners, although covered only with a shallow layer of lime and soil. When the bodies began decomposing in the summer heat of 1942, they became exposed. Members of the *Schutzstaffel* (SS), the elite Nazi paramilitary group under Himmler, ordered prisoners to exhume the bodies and then assist with burning them, fueled by wood and gasoline. In 1943 when it became apparent that the Nazis were losing the war on the Eastern front, they prepared to retreat. SS personnel were ordered to exhume bodies from mass graves and burn them (Auerbach 1979:38–40; Browning 1998:141). *Einsatzgruppe* leader Paul Blobel was tasked with the following:

> [R]emoving the traces of executions carried out by the *Einsatzgruppen* in the East… [and he] spent a grisly summer at Chelmno investigating fuels and systems for destroying masses of corpses. The bodies of the victims murdered in the gas chambers at Chelmno had been buried in mass graves. Blobel ordered them exhumed and used them in his experiments… he alternated bodies with railroad ties; then they were doused with gasoline or other flammable liquids.
>
> **(Browning 1998:259)**

In June-August of 1943, Blobel oversaw mass burial exhumations and the burning of bodies. At one site near Kiev, it took about two days to destroy the bodies in the grave. The same process was undertaken in Lithuania at Ninth Fort under SS direction: bodies were dragged from the grave and laid out in layers on the ground, alternating with layers of wood, with all drenched in gasoline (Browning 1998:260).

It seems that burning is attractive to organized killers initially, perhaps as a panic-response to early massacres where the desire is to eliminate traces of victims' remains and impede their identification. The time and resource costs, as well as the obviousness of such acts during the actual combustion, however, are quickly realized, and mass perpetrators tend to abandon body burning as a consistent body disposal method except when deemed urgent.

Postburial Treatment of Victim Remains

The example above illustrates how mass burial was the first choice of victim disposal for the Nazis, and only when they were losing territory and desperate to eliminate evidence of their crimes did they resort to the burning of bodies. This activity of postburial exhumation and alternative disposal of victim remains is not unique to the Nazis in latter stages of WWII. Fischer (2005) described the political controversy that surrounded the NKVD murders and mass burials at Katyn. During and following the war, the Soviets insisted that the victims were from Nazi massacres. According to aerial photoreconnaissance imagery, the NKVD bulldozed the area and removed some bodies from the graves sometime between 1941 and 1944.

The best-documented evidence of postburial treatment of remains in the context of armed conflict comes from grave excavations in Bosnia from 1996 to 2001. Much of this evidence has been presented at trial at the ICTY. In July 1995 up to 8000 men and boys from the enclave of Srebrenica, in western Bosnia, were taken prisoner by Bosnian Serb military forces. Over the next few days, they were systematically executed and buried in multiple mass graves throughout the local area. In October 1995, when the United Nations began to investigate the whereabouts of the missing, the killers coordinated a series of grave “exhumations,” removing bodies from the primary burial sites and relocating the remains to more clandestine locations. Over the next six years, archaeologists and anthropologists assisted the Office of the Prosecutor of ICTY to locate and excavate primary and secondary graves containing the remains of those missing from the Srebrenica massacre and others (Manning 2000; Skinner and Jessee 2005; Tuller 2012; Wright 2010).

Manning (ICTY 2003) also noted that an empty pit at the Zeleni Jadar site, near Srebrenica, probably indicates that a tertiary grave exists elsewhere, as other burials at that location were demonstrated to be secondary sites. According to Manning (2000), the empty pit was a robbed secondary burial. The archaeological and other investigative evidence (shell casings, blindfolds, ligatures, soil, pollen, glass from a bottling factory, and other artifacts) successfully linked execution sites with primary and secondary burial sites. In total, over 50 burial sites have been linked to the Srebrenica massacre (Reddick 2006:149). Thus, killer logistical behavior is extremely well-established in this series of cases: from the point of victim detention, to execution, primary burial, criminal exhumation, secondary burial, and finally exhumation as part of a medicolegal investigation. The Zeleni Jadar site is significant, because its geographical characteristics differ significantly from the primary sites, which are along major roads and tend to be in more open areas (e.g., fields). The locations of secondary sites reflect the deliberate effort to hide the bodies better from investigators: off tertiary roads, farther from populated areas, and more often in forested areas.

Political sensitivity to international investigations inspired a more complicated body disposal method in Bosnia. The availability of resources (transportation, fuel, and personnel under a chain of command) of the Bosnian Serb armed forces enabled them to employ this method. In some respects, the removal of bodies from Kosovo to Serbia in 1999 can be seen as an extension of this pattern. Once NATO began bombing Kosovo and Serbia and it was clear that the Serbs would be abandoning Kosovo, they removed bodies out of the territory altogether for secondary and subsequently tertiary burial. The scale of individual killing events appears to have been much smaller in Kosovo than Bosnia, but this may be a reflection of a more rural population in Kosovo as well as an example of “lessons learned in Bosnia” by Serbian military and paramilitary who were responsible for the majority of the killings in Kosovo. By keeping killing events frequent but with fewer individuals per event, the large mass graves containing hundreds of victims that were found in Bosnia would not be found in Kosovo. The change of tactics in the Balkans seems quite similar to the evolution of the killings in the Spanish Civil War Nationalist rearguard (see “Case Study: Killings and Body Disposal during the Spanish Civil War” section, below).

Skinner et al. (2002) noted that postburial disturbance may not necessarily be the result of perpetrators trying to hide evidence. There are some instances in which bodies are traded by opposing militaries or unilaterally handed over during and following conflict, those that are exhumed for preliminary forensic analysis and also those that are exhumed by family members. Skinner et al. (2002:297–306) observed examples of all of these in the former Yugoslavia and emphasized that distinguishing one type of postburial disturbance from another can be very difficult, particularly when exhumations fail to employ standard archaeological methods.

Holland et al. (2002) discussed causes of alterations of human remains and related burials from armed conflict in Southeast Asia. Although there has been a question on the motive for osseous alterations and whether it was criminal in intent, the most common explanation is carelessness or naive discovery and curation. In other instances, illegal bone trading is responsible. In this latter instance, the intention for the modification is not to hide criminal acts. Rather, acts such as dividing remains into smaller pieces potentially to increase the profits from their sale motivate illegal activity unrelated to the circumstances of death of the individuals' remains.

"Noncriminal" postburial disturbance has also been seen in Iraq, where, following the disruption or fall of Iraqi government authority in 1991 (Gulf War) and 2003 (Operation Iraqi Freedom), families and community members of victims went out to search for graves (Bouckaert 2003; Hess 2004; Recknagel 2003). Given the political sensitivity of such acts, they may have been done very quickly and relatively discretely. Like criminal postburial transfer of bodies, however, the family-organized exhumations in Iraq seldom involved the use of archaeologists and anthropologists. As such, traces of the original burials and human remains probably exist. Personal experience of the author in various countries has shown that inexpert grave excavations and exhumations typically leave significant traces of burials in the form of residual *in situ* human remains, traces of decomposition fluids, burial artifacts, or undamaged portions of the burial feature.

Body Disposal as Part of Systematic Repression

It is unclear if coordinated killings and body disposal in times of less organized and more protracted, low-intensity conflicts result in patterns that resemble those that occur in full-scale war. This is unfortunately the situation despite decades of forensic archaeological and anthropological work in Latin America, where conflict generally has been characterized by government or government-sponsored (e.g., paramilitary) forces combating less organized and less formal enemies over prolonged periods of time. Unconventional armed groups may not have uniforms, and membership may be loosely defined or organized. In fact, this is likely one reason why civilians are so often victimized in such contexts, as it is difficult for formal government armed forces to define who is an enemy and who, therefore, is considered a legitimate target. Although such killings as at My Lai in Vietnam (BBC 1998) and the massacre at El Mozote (Doretti and Snow 2003) in El Salvador might be cited as illustrations of this confusion, these incidents more accurately demonstrate how offenders use such "confusion" as a way of attempting to justify intentional killing of civilians. Nevertheless, in prolonged periods of armed conflict or repression, killers are constrained by similar logistic, geographic, and sociopolitical factors that greatly influence how and where victim bodies are disposed. These constraints should result in similar modes and patterns of body disposal as in formal armed conflict and warrant further study.

Case Study: Body Disposal during the Armenian Genocide

The Armenian Genocide (1915–1916) led to the death of hundreds of thousands of Armenians. Yet, this genocide is only part of a long history of the Ottoman Empire's mass violence against Armenians and other Christian minorities (e.g., the Hamidian massacres, Assyrian genocide, and Greek genocide) (Morris and Ze'evi 2019). Between 1915 and 1923, an estimated 800,000 to over 1,000,000 Armenians perished in the region (Bijak and Lubman 2016). These deaths included periods of coordinated large-scale massacres as well as deaths caused by conditions in concentration camps, torture, and forced marches through harsh environmental conditions without access to food, water, or medical treatment (Ferllini and Croft 2009).

From 1915 to 1922, Misak Seferian was a direct witness of death, murder, and body disposal. He created contemporaneous notes as he documented his experience of forced marches, escapes, armed battles of resistance, time in custody, and forced servitude. In translating and compiling these notebooks, his daughter and co-author Pearl Seferian made available a rich primary source based on eye-witness accounts of systematic violence against the Armenian population (Seferian 2015). Observations in these notes provided pertinent and yet untapped insights into human impacts on the taphonomy and modalities of body disposal.

During the Armenian genocide, body disposal depended on several confounding variables including the identity (social status, sex, etc.) of victims and the temporal stage of the crisis and location of death. Generally, male community leaders were killed in the early stage of persecution, which allowed for some of them to be buried by other community members. Women, children, and very young men such as Seferian's father were allowed to survive these initial waves of killing. In a second stage, there was mass displacement of the remaining Armenian community through forced "death marches". There are two principal important factors to consider here: (1) the terrain across which marches were taking place and (2) the protracted, low-intensity of the killings relative to the overall population being expelled. Many of those being expelled, were walking along "wild, mountainous regions, at average altitudes of 2,000 metres" (Kévorkian 2014:90). The narrow mountainous trails and valleys worked to hide not only the expulsion of hundreds of thousands of people, but also the thousands who died or were killed along the way, many bodies simply being left on the surface (Seferian 2015:31).

Civilians were thrown into rivers, lakes, and sometimes off cliffs. In the Ottoman Empire, this was done not only to dispose of (or simply displace) bodies, but also to kill them. Seferian (2015:14–15) recorded multiple instances of bodies being thrown into rivers. One incident described the author's brother's escape from a mass execution on the bridge of Aslé, near Handres. Approximately 400 victims were being shot and thrown into the river, but he fell into the water before being shot and swam to safety. In another instance, Seferian (2015:44) observed the daily killing of elderly and ill arriving in caravans on a bridge to Palu—their bodies on the bridge were disposed of in the Murat River. Kévorkian (2014:92–95) reported victims as having been tied together before being thrown into the Euphrates River to ensure that they could not swim to safety. There are parallels here with the tactics of the Argentina military in 1977 and 1978 methods of killing thousands by drugging them and throwing them out of aircraft into bodies of water (BBC 2005). In both cases, bodies later washed ashore.

Kévorkian (2014:95) noted that the documentation of corpses by foreign diplomats triggered an order to bury bodies deep enough so that they would not be scavenged. A similar reaction in Spain by the nationalists was observed after the massacre of Badajoz, and burning of bodies had been reported by international journalists (see "Burning of Bodies" section, above). Nevertheless, the sheer number of Armenian victims made their burial impossible. In addition, in inaccessible regions there were few resources to conduct burials and little perceived need to—there would be no investigations. In addition to logistics and impunity, a third element helps us understand a lack of burial: dehumanization. Co-author Seferian observes that the dehumanization of victims is common in genocide and interacts with killers' sense of impunity and resulting body disposal—there is no reason to hide something that would not be considered wrong.

Burial, however, did become more common for victims of the latter stages of the genocide when the expelled population was being held in concentration camps in places like Zor, Syria. Here, "burial committees" were tasked with disposing of dead. The dead from the camps often died of disease or hunger, and so other deportees and families could bury them. This might explain why some burials discovered during archaeological excavations in Syria in 2007 that stumbled upon apparent victims of the genocide appeared to have been buried respectfully (e.g., supine, with hands crossed over the body, and with apparent clothing) (Ferllini and Croft 2009). The greater numbers of females in these burials excavated by Ferllini and Croft (2009) is also consistent with Seferian's observation that men were more likely to be killed in their home villages before the forced marches and detentions at concentration camps.

Burial for those who died at camps, however, did not entirely replace the disposal of the dead in the Euphrates and Tigris rivers or even simply leaving bodies on the surface in the desert. The first and last of these modes would eventually enable a "final" taphonomic alteration, though one motivated by care, rather than cruelty: memorialization. Semerdjian (2018) included images of the bones of alleged victims as memorialized in the Martyr's Church at Dayr al-Zur in Syria. This posterior collection, display and memorialization of remains has, of course, many precedents, including in Cambodia (Fleischman 2016), and is a subject well represented in the literature that we will not elaborate here.

The Armenians suffered a fate not unlike those of the Polish, Byelorussians, or the Ukrainians during the Second World War, as described at the beginning of this chapter: trapped between and victimized by great powers. Having survived the forced expulsion marches by the Ottoman Empire, Misak Seferian joined the resistance movement in Armenia against the Bolsheviks. He was eventually imprisoned in Georgia, where he described something very similar to what Kamenetsky described above about killings in Ukraine under the Soviets, also similar to the *sacas* in the rearguard in Spain (see "Case Study: Killings and Body Disposal during the Spanish Civil War" section, below): prison authorities would arrive with a list of names and take prisoners out in groups. They would be systematically shot close to the prison, as noted by Seferian who listened to the cries of the prisoners and the shots soon after they had been removed from their cells at Tiflis (Tblisi, Georgia) (2015:251–273). Misak was then transferred to a prison at Alexandropol (Gyumri, Armenia) for questioning, but escaped with the help of the underground Armenian resistance. It is believed that executed prisoners were buried there also (Figure 10.1).

Case Study: Killings and Body Disposal during the Spanish Civil War

The study presented here sets a precedent by examining burial sites on a macroscale and as a series, and not as isolated features. The patterns evident in Spain may also be reflected in other contexts: different types of armed conflict (e.g., civil war or interstate war) in other countries and under quite different sociopolitical circumstances.

The war in Spain started in 1936 as a military coup, soon turned into a full-scale civil war, and quickly evolved into a systematic repression by the Nationalists who supported the coup. Even with Nationalist victory under General Francisco Franco in 1939, the conflict continued with the fighting of guerrillas and the detention and killing of other unarmed, perceived ideological enemies. Organized, state-sponsored killings and body disposal

Figure 10.1 The courtyard of the Bolshevik prison in Alexandropol (Gyumri, Armenia), where author Seferian's father was held prisoner. (Image by P. Seferian.)

continued in Spain for years after the formal, large-scale conflict had ended—much like what we see in more recent conflicts in Latin America.

A variety of body disposal site types were used in the Nationalist rearguard of the Spanish Civil War (including preexisting features such as wells). The use of cemeteries as killing and burial sites was quite common, particularly at the beginning of the war, or when the territory was freshly captured by Nationalist forces (see below). The use of "cemetery" in the context of Spanish Civil War killings, however, is contentious. Many people in Spain and in the documentation from the time of the killings employ this term (*cementerio* in Spanish). In a strict sense, a modern cemetery is a formally recognized and legal burial place. In times of large numbers of deaths, alternative areas may be used to dispose of bodies, and they become—officially or unofficially—cemeteries. Remote areas of formal cemeteries or even plots of land adjacent to cemeteries or on the property of public or religious grounds may be used as mass burial sites (e.g., Congram et al. 2014). In the situation of illegal killings and burial, the label of "cemetery" may also be used to "protect" burials, which is to say prohibit investigation, because of the special status of cemeteries and the general taboo of removing remains from them. In such instances, archaeological expertise is often necessary in distinguishing legal from illegal deaths and burials (Figure 10.2).

Two types of rearguard killings predominated in Spain and resulted in clandestine victim burial: *paseos* and *sacas*. Zavala (2006) traces the use of *paseo* to the American mafia of the 1920s and 1930s and their euphemistic use of the term "stroll" or "walk" (e.g., "Let's take him for a walk"). *Sacas* ("to take out, to remove") appear in official documents showing that prisoners were released, but upon exiting the front gates, trucks with paramilitaries or civil guards would be waiting to drive the prisoners to their place of extra-judicial execution (Rilova Pérez 2001). Zavala (2006:95) distinguishes between these two types of killings by calling *sacas* "industrialized" versions of *paseos*, meaning that they demonstrated greater coordination by the authorities and produced larger numbers of deaths per

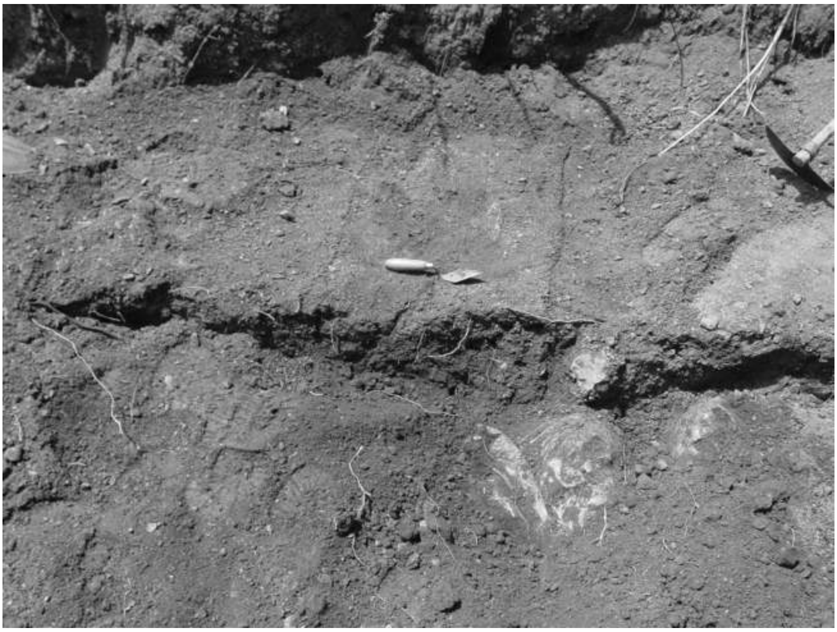

Figure 10.2 Modern mass burial cross-cutting legal cemetery burial. The partially excavated mass burial runs left to right and intersects an older legal burial (center of photograph) that conforms with cultural norms related to the depth, size, and orientation. The trowel points north.

killing event. *Paseos* and *sacas* committed by the Nationalists in Spain were strategic, preemptive killings of perceived ideological enemies (Herreros and Criado 2009).

Research on killings during the Spanish Civil War shows an evolution of body disposal methods that appears to be a response to sociopolitical sensitivity about the deaths, based in part on symmetry of control in an area. In the first weeks of the attempted coup, executions were more commonly done in public places. As a failed coup turned into civil war, and parties fought to garner support from both the public and international partners (or at least stave off intervention that would hurt their cause), killings became more clandestine (Castro 2006:220; Congram 2010; Vilaplana 1977:87, 170).

Kalyvas (2003, 2006) analyzed the dynamics and mechanisms of violence in civil war, specifically under what circumstances civilians are targeted and killed by authorities. Congram (2010) built upon this to examine the dynamics of victim disposal once they have been killed. A key observation of Kalyvas (2003, 2006) is that where a group in a civil war is contending for control, the degree of selective violence that it employs is directly related to the level of control that they possess in an area and the persuasion they can employ on potential informants who provide the vying authorities with targets for their violence. The pattern observed by Kalyvas (2003, 2006) is parabolic when one plots the degree of control along the x-axis (with one contending group at one end of the scale and another group at the opposite end of the scale) against the use of selective violence along the y-axis: when one group's political control is great, the need for and the use of selective violence against the civilian population are low; when control is threatened, violence increases; and when two sides seem to be vying equally for control, the general population avoids taking sides, and contending authority groups avoid violence against the general population for fear of turning people against them. Following this logic, how bodies are disposed of will depend in part on the degree of control that the killers have over the territory in which the killing takes place and the sensitivity of these killings.

The evolution of killings by Nationalist forces in Spain seems to have gone through three general phases:

1. An initial, more anarchic, though deliberate stage of large-scale killings by military forces as they moved into new territory. The most notorious examples of these are large-scale killings at cemeteries in Andalusia (Gibson 1973; Jackson 1965:299–300; Zavala 2006:272) and the machine-gunning of prisoners in Badajoz described above (Espinosa 2007:371). These killings generally occurred immediately following the conquest of populous territory and were committed by the advancing troops, partly as a means of protecting the military from having to return to combat continuing resistance in the previously conquered territory (Armengou and Belis 2004:37–38; Jackson 1965:536).
2. Over the first four months following the attempted coup, the predominant form of killing (far exceeding battle casualties; Bahamonde 2005:139; Bennassar 2005:102; Castro 2006:250; Jackson 1965:533) was targeted, more covert executions of civilians by the Nationalist rearguard, mostly by *Falange* paramilitary. The killings during this phase are characterized by *paseos* and *sacas*, whereby people were detained at their homes or taken from prisons at night, driven out of urban areas, and shot at roadside locations. Castro (2006:220) reported that these were the predominant forms of killing, and in little over two months, 26 *sacas* produced at least 400 deaths of prisoners from the Burgos Central Prison alone. Castro (2006:221) calculated that *paseos* and *sacas* accounted for at least 75%–80% of all deaths in Burgos (where the coup was largely successful) in the first three months following the coup.
3. A consolidation and formalization of political and military authority under the *Generalissimo* Francisco Franco took place in the late autumn and winter of 1936. Following this, courts martial were imposed, and killings were preceded by mass incarceration, group "show trials" lasting only minutes, mass sentencing, and formal, "legal," or legitimized executions (Espinosa 2007:402; Rodrígo 2008). This last phase would become the dominant mode of killing from 1937 and beyond the end of the civil war and has been referred to as the "institutionalized repression" (Prada Rodríguez 2006:202–295). This repression is said to have been instigated by foreign allies of the Nationalists (presumably the Nazi Germans and Fascist Italians; Vilaplana 1977:87, 170), probably due to sensitivity of negative press related to the less formal mass killings (e.g., Martín Barrio et al. 1988:373). Given the legitimized nature of the killings at this stage, they would more often take place publicly, or at least not in the clandestine form of *paseos* and *sacas* of the second stage of the repression (e.g., Torres 2002:247).

The second phase of the repression is of interest and relevance to the present study. The killings from both the first and third phases were more likely to result in cemetery burials (e.g., Botella López, pers. comm. on Andalusia; Rilova Perez 2001 on Burgos).

The aim of the study upon which this section of the chapter is based (Congram 2010) was to identify patterns of killers' behavior. This information could then be used to facilitate the search for further graves of victims of rearguard killings. The sample for the study

Table 10.2 Independent Variables as Recommended for Consideration during Stages of Investigation

Variable	Used for Predictive Model (Stage 1)	Used as an Investigative Guide Based on Statistical Analysis (Stage 2)	No Significance Detected
Number of victims		X	
Distance traveled		X	
Road side (L/R)			X
Road type	X		
Distance from last town*	X	X	
Distance to next town**	X	X	
Towns crossed		X	
Distance from road to grave	X		
Population density relative to sites		X	

*, ** Distances between the grave and the populated areas on either side of it were taken as a single variable in the predictive models: included as a population layer and the measurement of the *single* nearest populated areas was modeled. These two variables should also be considered in the second investigative stage independently based on the results of the descriptive statistics.

included data from 44 excavated burial sites of victims of Nationalist rearguard killings, mostly from the last half of 1936 (the first six months of the war). Frequency statistics were calculated on several variables relative to burial locations, and other variables were used to create suitability maps, which highlighted areas of greater and lesser suitability for burial based on landscape characteristics. These maps were based on three predictive models using either inductive or deductive approaches. Table 10.2 lists which variables were examined, according to this study, and in which way.

Among other things, the results of this study demonstrated that killers traveled to foreign and lower-density municipalities before shooting their victims. This trend is particularly useful to investigators, as it indicates that witness and archival information related to killings is more likely to be found in municipalities that surround that of the victim origin. Generally, unless burials were conducted in cemeteries, there appeared to be a buffer around populated areas, showing that killers preferred to travel a certain distance beyond towns before killing. Even for cemetery killings, the cemeteries chosen were often located a short distance outside of towns.

Prior to being able to employ the results of this study's work, one should identify the incident type that resulted in a disappeared person or persons to ensure that it is consistent with the killing incident studied (*paseos*). One also must ensure that there is little or no possibility that the victims were interred in or around a previously existing cemetery local to the detention site. This should be done by examining cemetery and local government and church registries (including both religious and civil burial sites). Surprisingly, work by historians has shown that despite the criminality of the killings, many victim burials were registered in one form or another (Espinosa 2009). Of equal if not greater importance, investigators should conduct directed questioning of local populations, who have sometimes proven to be valuable sources of information, even 75 years after the majority of the killings (Gómez and Junquera 2008).

If cemeteries and preexisting features appear not to have been used as body disposal sites, then the following guidelines can be used to search for the victim grave in a two-stage investigative process. The predictive model that performed most accurately to create a suitability surface is used in "Stage 1" of the guidelines and is based on area road types, distances from roads, and distances from populated areas relative to the victim origin (i.e., the point of detention by the killers).

"Stage 2" is based upon the results of other variables analyzed using univariate and bivariate tests of statistical significance and descriptive statistics. The second stage considers information that could not be modeled and involves creating two prioritized probability areas, labeled "a" and "b" according to higher and lower probability, respectively (within the high suitability area). Probability area "a" includes 67% of the cases from the study sample according to the values of the independent variables. Probability area "b" includes 95% of the cases according to the values of the independent variables. As the independent variables used for this second investigative stage demonstrated strong positive skewness, the cases considered for each of the probability areas were taken around the median. Independent variables considered here include "distance traveled", "towns crossed". "distance to last town", "distance to next town", "land-use/cover", and "population density". Sites discovered to date show that these can be expected to be within 200 m of a road, although most will be within 100 m.

Stage 1 will examine the suitability map and identify the high suitability area within 50 km of the origin site.

Stage 2 will take place entirely within this high suitability area.

Higher probability area "a"

1. Distances within 14.5 km of the origin.
2. Along roadways between the origin and the next two towns in all directions.
3. Areas between 350 m and 3.12 km of all towns passed in the direction of travel (assuming no other towns are crossed).
4. Areas between 4 km and 250 m of all towns being approached in the direction of travel (assuming no other towns are crossed).
5. Property that was farmed at the time of victim disappearance (orchards, vineyards, and fields).
6. Municipalities with a lower population density than the origin.

Lower probability area "b"

1. Distances within 36.15 km of the origin.
2. Along roadways between the next two to six towns in all directions.
3. Areas between 250 m and 9 km of the last town passed in the direction of travel (assuming no other towns are crossed).
4. Areas between 12.3 km and 350 m of all towns being approached in the direction of travel (assuming no other towns are crossed).
5. Areas of all but heavy cover (i.e., forested) at the time of victim disappearance.
6. Municipalities with population density equal to or less than the origin.

These investigative guidelines obviously are meant only for the discovery of primary disposal sites. There are instances of both "criminal" and "noncriminal" body removal from primary sites during and following the Spanish Civil War.[3] There is limited oral evidence of clandestine grave exhumations by victim family members during and soon after the war

(M. Molina, Co-Director of the Cuenca Chapter of the Asociación para la Recuperación de la Memoria Histórica, pers. comm.). Following Franco's death, and during a transition to democratic governance in Spain, limited exhumations of victims of Nationalist killings were conducted by families of the victims without legal mandates or support (Baviano 1980; Ferrándiz 2009:83–85; Herrero Balsa and Hernández García 1982; Silva and Macías 2003).

Postburial exhumations and body transfers also occurred at the behest of the Franco government during the 1950s. Having carved a massive memorial—the "Valley of the Fallen"—out of a mountain, using prison labor, the government set about exhuming those who were killed or died fighting for the Nationalist cause. The inflated number of victims propagated by the Nationalists during the war came to light and resulted in much empty space at the memorial. The government's solution was to exhume victims of Nationalist execution and bury them at the Valley of the Fallen as well. Many of the families of the victims of Nationalist killings were unaware of the original clandestine burial sites and so were equally ignorant that the bodies had subsequently been relocated to the monument honoring their killers. Only through recent investigations have family members come to realize that the victims do not lie in anonymous mass graves near their place of disappearance but at the war monument that Franco had built for those who died fighting for the Nationalists (Barcala 2010). In May 2011, the Spanish government announced that identification of those interred at the Valley of the Fallen would be impossible (Barcala 2011). This reconcentration of remains has precedent in prehistoric and historic contexts (e.g., Olson 1966), as well as in the animal kingdom (Chapter 9), although the motivation for the behavior obviously can differ greatly both on an inter- and on an intra-species level.

Criminological Study of Peace-Time Serial and Individual Murder

Early examples of criminological studies, as exemplified by the Chicago School (Becker 1999), adopted an ethnographic fieldwork approach to studying urban crime and relating human behavior to ecological factors. More recent criminological work, particularly by those in environmental criminology and offender profiling, has analyzed geographic patterns of offender movement in cases of individual murders and serial murders in a "peace-time" context. Lundrigan (2016) provided an overview of the spatial behavior of murderers and "locational logistics of murder" and how this can inform the search for missing victims. Comerford (2021) presented a review of the literature on geographic mobility in serial homicide cases, noting a lack of systematic research and providing recommendations for geospatial analysis. The focus of these studies is on the mindset and behavior of murderers and how this is manifested geographically, as in offender residence relative to offense locations. Such lines of inquiry are of obvious relevance to forensic anthropologists and the study of *H. sapiens sapiens* as a taphonomic agent. Although the conventional forensic anthropologist is more likely to be concerned with the geographic information that comes from these studies (e.g., knowing where and how murderers tend to dispose of their victims), the study of killers' thought processes and activity is within the realm of broader anthropological study as discussed at the beginning of this chapter.

Much of the criminological study on body disposal involves the use of several principal concepts including the distance decay effect (Rengert et al. 1999; Rossmo 2000), which relates to Tobler's first law of geography (Sui 2009). Tobler's Law states that things that are nearer in space are more similar, or have stronger relationships, than things that are more distant (also referred to as spatial autocorrelation). Rossmo (2000:211) presented a thorough overview of criminological work on geographic analysis of offender behavior, which culminated in geographic profiling, which he referred to as "a strategic information management system designed to support serial violent crime investigations."

There is significant variation in victim disposal patterns among murderers, and some of this variation is dependent upon the nature of the crime (e.g., sexual or emotional), offender (e.g., individual or serial murderer), and the victim (e.g., child or adult). Disagreement also exists among researchers about the validity of various categories of murderers (e.g., "organized" versus "disorganized"; Canter et al. 2004; Ressler et al. 1986). Distinguishing patterns according to the many groups and criteria is akin to trying to isolate the relative influence of individual factors in human decomposition: the complex interplay of many variables makes the extraction of meaningful information about a single variable extremely difficult.

Kraemer et al. (2004) studied 157 serial homicide offenders with 608 victims and compared a subsample of serial homicide offenses with a control group of single homicide offenses. They observed that serial homicide offenders kill from apparent sexual motivation more often than for any other reason, while single homicide offenders kill most often out of anger. Perhaps the impulsivity of single homicides versus the planned serial homicides helps explain the observation made by the authors that for single homicide offences, different elements of the crime (the initial contact site, the murder site, and the body disposal site) tend to be at the same location, whereas these elements tend to be distinct sites for serial homicides. Kraemer et al. (2004:335–336) further noted that "The only significant difference in method of body disposal was the increased likelihood that serial homicide offenders dump the body in a remote location".

Reinforcing the parallels between human and nonhuman animal behavior asserted in this chapter, Kraemer et al. (2004:327–328) concluded the following regarding single and serial murderers:

Borrowing from ecological biology models, it can be observed that animals kill for two reasons: competition and predation (Lord et al. 2002). Most homicide offenses are between two males who know each other and can be understood as eliminating competition of peers (Daly and Wilson 1988). Serial homicide offenders, however, although also predominantly male, more frequently target women and children who are strangers. Killing such victims may be a form of predation, to acquire a desired resource such as sex.

Although several studies demonstrated some differences between serial and single homicide offender motivation and behavior, including travel patterns for victim disposal, there are many similarities when victims are not left in the home of the offender or victim. Table 10.3, adapted from Lundrigan (2016), presents the results of distances between residences, encounter sites, and body disposal sites for multiple studies, including several of those discussed below. The studies are arranged by country first, then by homicide type.

Serial Murder

Serial murder is very uncommon, despite its ubiquity in fiction. Killers show trends in victim body disposal behavior, but some studies also show that killers adapt their behavior over time as they kill. Adaptation to circumstances and the complexity of human decision processes and behavior (including those killers who suffer a degree or particular form of psychopathy) frustrate investigative efforts to classify and model patterns. Nevertheless,

Table 10.3 Distances to Body Disposal Sites in Multiple Studies (Adapted from Lundrigan [2016])

Source	Crime	Location	Origin Location	Destination Location	Crime Trip Distance
Godwin and Canter (1997)	Serial murder	US	Offender base	Encounter (location where perpetrator first encounters victim) BRS	Mean = 2 km
Rossmo (2000)	Serial murder	US	Offender base	Encounter BRS	Mean = 22 km Mean = 34 km
Lundrigan and Canter (2001a)	Serial murder	US	Offender base	BRS	Median = 15 km; mean = 40 km
Safarik et al. (2000)	Sexual homicide elderly females	US	Victim's residence	BRS	56% within six blocks of victim's residence
Hanfland et al. (1997)	Child abduction murder	US	Victim's residence	BRS	37% cases < 2.4 km
Brown and Keppel (2007)	Child abduction murder	US	Victim last seen	BRS	46% < 1.5 miles (2.4 km)
Van Patten and Delhauer (2007)	Sexual homicide	US	Victim's last residence	BRS	Median = 4.62 miles (7.4 km); mean = 56.92 miles (91.6 km)
Bullock (1955)	Homicide	Houston	Offender base	BRS*	40% <1 block 57% <0.4 miles (0.68 km) 74% < 2 miles (3.2 km)
Keppel and Weis (1993)	Single murder	Washington State	Victim last seen	BRS	76% < 200 feet (61 m)
Rand (1986)	Criminal homicide	Philadelphia	Offender base	BRS	53.1% within home census tract
Nethery (2002)	Homicide	Canada	Victim's residence	BRS	Mean, child victim = 10 km; adults = 30 km
Andresen et al. (2014)	Homicide	Canada	Offender base	BRS	Median = 0.66 km
Gabor and Gottheil (1984)	Homicide	Ottawa	Offender base	BRS	Mean = 0.54 miles (0.87 km)
Aitken et al. (1994)**	Child sexual homicide	UK	Offender base	BRS	91.6% <5 miles (8 km)
Shaw (1998)**	Sexual homicide	UK	Offender base	Encounter BRS	Mean = 2.4 miles (3.86 km) Mean = 2.2 miles (3.54 km)
Dern et al. (2004)	Serial murder	Germany	Offender base	BRS	58% < 5 km
Snook et al. (2005)	Serial murder	Germany	Offender base	BRS	63% < 10 km, median = 6.5 km; mean = 30 km
Santtila et al. (2007)	Difficult to solve homicide	Finland	Offender base	BRS	Median = 0.85 km
Santtila et al. (2008)	Difficult to solve homicide	Italy	Offender base	BRS	Median = 0.98 km; mean = 15.98 km

* BRS = Body recovery site

** As cited in Lundrigan (2016)

Table 10.4 Attempt to Hide Victim Body by Serial Killers

Characteristic	% (Number)
Displayed	7.3 (13)
Dumped	10.7 (19)
Other, not hidden	34.3 (61)
Casually hidden	10.1 (18)
Well hidden	25.3 (45)
Other	12.4 (22)

Source: Rossmo (1995).

certain information can be derived from these studies that assist with crime resolution, including victim discovery and identification.

In developing geographic profiling, Rossmo (pers. comm.) studied patterns of serial murderers, which included data on victim body disposal sites (n = 104). The body disposal site area was "residential" (as defined by city maps and/or as reported in various crime documents) in almost half of the sites analyzed (45.2%, with almost 17% actually at the offender residence). The next highest category of disposal site type was, ironically, the opposite: "wilderness or uninhabited" (21.2%). The dominance of these two very different location types illustrates the great variability of locations selected by serial murderers. Slightly over 20% were categorized as "river, lake, or marsh." Almost three quarters of disposal sites were outdoor, public places (Rossmo 2000:175). Table 10.4, adapted from Rossmo (1995:317), shows the variation demonstrated in attempts to hide (or not) victim bodies. As with body disposal location type, there is little consistency in attempts to hide victim bodies.

The mean distance of body dump sites from victim-offender encounter sites was 11.9 km. Remarkably, this result is very consistent with the distances between detention and body disposal sites from the above study of burials from the Spanish Civil War rearguard (mean distance between victim-offender encounter and burial location of 13.11 km, 67% of burials within 14.5 km). However, the standard deviation of this distance measure in Rossmo's (2000) data is high (25.9 km). It should be noted here that the distribution of these data—in studies by Rossmo (2000) and others—is seldom normally distributed, so both the mean and the standard deviation can be misleading. Rossmo (2000:176) noted that "optimal body disposal sites are often situated in uninhabited regions located some distance from urban areas", although this seems to stand in contradiction to the high frequency of residential area disposal sites selected (as well as some disposal sites being in the home of the offender) in his study.

A further observation made by Rossmo (2000) is that serial killers tend to mimic the hunting behavior of certain nonhuman predators by repeatedly visiting the same sites, which includes revisiting body dump sites. Although Rossmo (2000:179) suggested that this behavior is motivated at least in part by offender fantasies, it is also reasonable to believe that once killers have found a "good" body disposal site, they continue to use it. Site reuse has been seen in the context of armed conflict, as evidenced by the agglomeration of secondary mass burials of Bosnian Muslim victims in the area of Zeleni Jadar as discussed above or the continued mass killings and burials in the forest north of Granada or throughout Burgos province during the Spanish Civil War (Gibson 1973; Jimenez, pers. comm.). Just as nonhuman animal behavior demonstrates the repeated use of geographic and ecological space regarding remains transport (Chapter 9), so too is *H. sapiens sapiens* a creature of habit.

Godwin and Canter (1997) studied the relative distances between offender homes, the "point of fatal encounter" between offender and victim, and the body dump sites of victims of 54 male US serial murderers, each convicted of at least 10 murders. They concluded that the data demonstrated a consistent effort to dump bodies beyond the point of first encounter, which is to say farther away from the offender's residence than the point of encounter. They also noted that serial murderers appear to spread the location of dump sites (i.e., subsequent disposals in the opposite direction as the previous disposal), possibly as a means of reducing the risk of detection. The mean distance between offender residence and body dump site was 22.9 km, with a standard deviation of 8 km. The mean distance from the point of first offender-victim encounter to the body dump site was 20.5 km, with a very small standard deviation of 2 km. It is surprising that these results are quite different from those of Rossmo (2000), particularly because the datasets certainly included many of the same offenders and sites. Some of this gap can be attributed to different sample criteria: Godwin and Canter (1997) studied those with at least 10 victims, while Rossmo [2000] analyzed murderers with at least five victims. Distinct analytical methods also were employed. Interestingly, Godwin and Canter (1997) documented a fairly consistent and significant decrease in distance between offender residence and body dump site with each consecutive killing. It is possible that confidence of the offenders in avoiding detection results in their committing less effort to dispose of victims as time goes on.

Snook et al. (2005) analyzed 53 serial killers in Germany. Unfortunately, they also used slightly different criteria from both Rossmo (2000) and Godwin and Canter (1997) for selecting cases for analysis. Also somewhat problematic for comparison with other studies is the failure by Snook et al. (2005) to distinguish among the victim-offender encounter site, the murder site, and the body disposal site. The only two locations examined were the offender base (typically his/her residence) and the body disposal site. Despite these differences, the overall results are informative and broadly comparable. Snook et al. (2005) reported a median distance between offender residence and body disposal site of 6.5 km. In this instance, the reporting of the median distance rather than the mean is most useful, as the distribution of distances is negatively skewed with a very long tail (i.e., a small proportion of very remote outliers of murderers who traveled very far to dispose of bodies). They concluded by saying that "German serial murderers generally dispose of their victims' bodies in close proximity to the murderer's homes… [and the distance] follows a decay pattern" (Snook et al. 2005:161), in accordance with Tobler's Law. Table 10.3 shows the percentage of cases relative to distances from offender residences as observed by Snook et al. (2005) for German serial murderers. Snook et al. (2005) did not attempt to explain the relatively short distances when compared with North American serial killer spatial behavior. One possible explanation is the greater population density in Germany, which gives killers few reasonably close unpopulated disposal sites. The possibility of a higher prevalence of urban or semi-urban parks within a larger high population density area in Germany as opposed to North America may make the parks the most reasonable choice for body disposal, and their relative ubiquity close to murderer residences would account for the shorter distances observed in Germany. Higher population density could also explain the long tail and very long distances traveled by only a few of those studied by Snook et al. (2005), as killers unwilling to dispose of bodies in an urban or semi-urban environment would have to travel great distances to go beyond urbanized areas. A final possible explanation relates to the sample size of the populations analyzed. In a study of US and UK serial murderers, Lundrigan and Canter (2001a) demonstrated that the distance between an offender's residence and body disposal sites generally increases with subsequent victims. This is the opposite of what was shown in Godwin and Canter's (1997) study discussed above, which calls their explanation (increasing killer confidence to avoid detection) into question. The study by Snook et al. (2005) included killers with a minimum of three victims and an average of five (247 victims of 53 murderers). Lundrigan and Canter's (2001a) study included those convicted of killing a (comparable) minimum of two victims, but the average was seven for both groups (898 victims of 126 US murderers and 207 victims of 29 UK murderers). It could be that the greater number of average victims per killer in the US and the UK explains some of the difference in distances. Nevertheless, distances from Lundrigan and Canter's (2001a) study showed a median offender home to body disposal site distance of 15 km (mean of 40 km) for US serial murderers and a median distance of 9 km (mean of 18 km) for UK serial murderers, which could also be interpreted as supporting the hypothesis posited here on the influence of population density on distances traveled to dispose of victims. Lundrigan and Canter (2001a) attributed the difference in distances in their study to topography and ease of travel, and this remains a further possible explanation. Although they do not explain what they mean by "ease of travel", this could be based in whole or part on relative measures of traffic congestion, which would reflect back on the influence of population density.

Other conclusions drawn by Lundrigan and Canter (2001a:595) included the observation that "the locations at which serial killers dispose of their victims' bodies reflect the inherent logic of the choices that underlie their predatory activities". They demonstrated that although a murder and its motivation may be irrational, the choice of victim disposal site is often rational and one that avoids immediate detection and apprehension of the offender. Table 10.3 shows the proportions of distances between US and UK serial murderer residences and body disposal sites.

Lundrigan and Canter (2001b:423) also analyzed serial murderers using the approach of environmental psychology, through which they surmised that although the murders committed may not be considered rational, "environmental psychology hypotheses predict that their choice of disposal site location may be guided by a recognizable rationality… evident through their spatial patterns of disposal locations." They found that the offender residence was central, spatially, to their choice of disposal sites. They also found that previous disposal site locations influenced subsequent location choices, although this influence was stronger for those whose geographic range was smaller. This could be interpreted as the short-range murderer being more concerned with avoiding detection and association of one murder to the next.

Salfati and Bateman (2005) examined serial murders and crime scene characteristics in an attempt to identify behavioral consistency, which could in turn be used to discern multiple crimes/crime scenes from potentially multiple offenders. Although many of the crime-scene behaviors observed are not relevant to the present research, the authors noted that in 65% of the cases that they studied, the victim body recovery site was indoors. They also observed that in 44.9% of cases, the killer appeared to be unconcerned with disposal of body, whereas in 34.8% of cases, the victim body was hidden or placed to prevent discovery. These results are similar to those of Rossmo (2000), who found that victim bodies were either casually or well hidden in just over 35% of cases (Table 10.4). As with other studies, this should not be surprising, as the cases examined and the criteria used by both

Rossmo (2000) and Salfati and Bateman (2005) are the same (i.e., an offender arrested for a minimum of three murders over time).

As part of a forensic search for victims, information about the nature of the crime—be it individual, serial, or mass murder—might affect how a search is conducted. Studies analyzing individual murderer behavior patterns and some comparing individual and serial murderer patterns are therefore critical to understanding the taphonomic signature of *H. sapiens sapiens* predatory behavior.

Individual Murder

Häkkänen et al. (2007) examined murder victim body disposal sites (n = 46) in Finland. They found that 73% of bodies were disposed of in wooded areas and 27% in water, although it is unclear if any other categories were considered for disposal site location. They restricted their study to victim disposal in rural areas of Finland. Nevertheless, they did report the distances among offender residences, homicide sites, and body disposal sites. The statistics on these distances can be loosely compared with those studies already mentioned above, measuring similar distances when disposal sites at victim or offender residences have been removed from calculations. Table 10.3 shows the proportion of distances traveled between homicide sites and victim body disposal sites for the cases examined by Häkkänen et al. (2007). These are relatively farther than distances in other studies, and this is almost certainly attributable in part to the sample criterion of rural victim disposal site.

In 20% of their cases, there was an attempt to burn the victim's body. Slightly over one quarter of victims were deposited within 200 m of a road, almost one half (43.9%) within 500 m, and 29.2% over 1 km from the nearest road. Although most other studies on victim disposal behavior do not report distances from road (for an exception, see the discussion of Manhein et al. 2006, below), this measure is of obvious use for investigators of missing persons. The measure of distance from the nearest road of burials from the Spanish Civil War (see "Case Study: Killings and Body Disposal during the Spanish Civil War" above) was made only indirectly, due to lack of reported detail of sites (e.g., datum used for recording global positioning system [GPS] coordinates). Nevertheless, personal experience of the senior author in this context, discussions with colleagues, and reference to photographs from the excavation reports demonstrated that burials of civilian victims executed in the rearguard were seldom more than 100 m from the nearest road, but it is reasonable to believe that those closer to roads are more likely to be discovered.

An interesting observation by Häkkänen et al. (2007) is that three of the five female victims in their sample were transported a relatively long distance for disposal (>50 km). This difference of treatment of female victims was posited in the study of Spanish Civil War killings, but a small sample size (victim groups that included at least one female in the Spanish study totaled three) meant that statistical significance of other variables related to female victims could not be reliably tested. A further important observation by Häkkänen et al. (2007) was that psychopathy in the offender showed no significant correlation with distance patterns, reinforcing the assertion that murderer behavior with respect to victim body disposal generally demonstrates rational thinking.

Lee and Park (2019) studied 104 cases in South Korea where offenders transported bodies from death scenes to other locations (compared with 409 cases where bodies were not moved). They observed that the movement of bodies had generally been planned in advance. They further noted that postmortem movement of victims was more likely when the offender and victim were family, speaking to the sensitivity of the killing and the desire to hide it.

Nethery (2002) studied abduction and murder victims of both serial and individual murderers in Canada and Washington state, USA. She observed that the majority of victims were killed in isolated and secluded areas, which most often served as the body disposal site, principally wooded areas. Child victims (less than 12 years old) also were sometimes disposed of on farmland or in bodies of water. Nethery noted that in most cases, body disposal was planned by the offender prior to the murder. Taking the victims to the disposal site while alive and killing them there facilitated body disposal. This was the *modus operandi* for the rearguard killings of the Spanish Civil War and during WWII, where truckloads of victims were often taken to prepared graves, where they would be shot and buried.

According to Nethery's (2002) research, in cities or towns with a population of less than 50,000, 50% of child victims were disposed of in locations over 25 km away from the victim's home (and the abduction point was within 3 km of the victim's home in all cases). In areas with a population greater than 50,000, only 16% of victim bodies were disposed of more than 25 km away from the victim's home. Further, in the largest city in the study—Toronto, with a population of 2.5 million—offenders traveled the shortest distances to dispose of victims' remains. Mean distances from the murder scene to the body disposal sites were 4 km for larger cities and 15 km for smaller cities. These data support the conclusion that offenders travel shorter distances in more urban areas, as seen in the studies of serial killers in Germany and the UK. This relationship is especially apparent considering that most victims' bodies in Canada are disposed of in isolated or secluded areas, meaning that these areas exist within very short distances of urban or residential areas where victims and offenders meet. Population density figures between 1961 and 2017 for Germany average 228 people/km^2; 240 for the UK; three for Canada; and 28 for the USA (World Bank 2021). To assess the possible influence of population density more accurately, however, one must consider the more local density in the areas of the murders. In the case of Canada, the overall population density figure is misleading, as a vast majority of the population is concentrated near the southern border with the USA, and this zone is where most serial murder occurs.

Also in Nethery's (2002) study, for young adult victims (13–17 years old) in Canada, 16 of 17 were disposed of less than 10.9 km from the murder site. Among adults (at least 18 years old), four of five were disposed of less than 5.9 km from the murder site. Though informative, confidence in this distribution is very limited due to small sample sizes.

Morton and Lord (2002) compared two studies focused on child abduction and homicide (Boudreaux et al. 1999; Hanfland et al. 1997). Overall, a clear majority of victims from both studies were disposed of less than 8 km from the victim's residence, and body disposal distances appeared to be relatively small for children, which is probably related to the nature of the crimes and relationships between offenders and victims, many offenders being related to or acquainted with their victim. Morton and Lord (2002) concluded that, generally, the younger the victim, the closer to the home their body will be found.

Van Patten and Delhauer (2007) studied 197 sexual killings in Los Angeles County, USA. As with other serial murder studies, their sample is skewed by a small proportion of murderers who traveled very long distances (e.g., the distance from one offender's home residence to the body dump site was 3411 miles, or 5457 km). Such cases should be treated differently so as to get a more realistic measure of general spatial behavior. For this and similar reasons, some researchers refer to an offender's "base", which may include a residence or another location at which they spend a significant amount of time (e.g., workplace) and from which they travel to commit murders. In the instance of outliers, it is probable that murderers have a local base that is unrecorded, leaving researchers to include an unusually distant residence instead. Specifically because of this bias inherent in the data, Van Patten and Delhauer (2007)—like other researchers discussed here—relied more on median distances rather than the mean. In a large proportion of cases (41%), the offender disposed of the body at the victim's residence. This is an important consideration for investigators of missing persons, particularly when offender sexual motivation is suspected. Nevertheless, removing these cases where no travel has occurred, the median distance from offender residence to encounter site was 2.67 km, and the median distance from offender residence to body disposal site was 3.9 km. The mean distance of encounter site to the body disposal site was 11 km, and the median distance was 4.2 km. Table 10.3 shows distances between victim-offender encounter site and victim body disposal site.

The Spatial Taphonomic Signature of *H. sapiens sapiens*

Listi et al. (2007) explored the use of GPS as a technique for mapping surface-scattered human remains but concluded that the inaccuracy of recorded locations of elements relative to one another makes traditional archaeological mapping techniques preferable. Manhein et al. (2006) used geographic information systems (GIS) and spatial analysis in Louisiana to examine possible patterns of where and when human remains are dumped as well as to determine if PMI correlates with distance of remains scatter and direction of scatter. They used the terms "spatial forensic taphonomy" and "geo-forensic taphonomy" to refer to the use of GIS and spatial analysis to answer taphonomic questions in forensic contexts. Unsurprisingly, they found that a significant number of body dump sites were within 400 m of a road and away from structures. Remains were also more likely to be found in wooded rather than open environments.

Apart from many limitations acknowledged by Manhein et al. (2006), there are several others that should be considered for those building upon what is a promising line of research methods. As this volume demonstrates (Chapter 3), PMI estimation is very complex, and precise intervals—particularly for skeletonized remains—should be critically examined. The data used in these analyses, as in all other similar studies, are biased toward the types of places in which remains are found (i.e., those that are less effectively hidden or placed in less remote locations and so more likely to be discovered). This explanation may account for the majority of dump sites appearing to be close to roads. The complete range of body disposal behavior is indeterminable in most cases, where the number of victims is unknown. In situations outside of armed conflict, a missing person is not necessarily a murder victim: they might have migrated elsewhere, died through another cause in a remote location, committed suicide or died of overdose, or be intentionally avoiding contact with others (Skinner and Lazenby 1983). Although these explanations are also possible for disappearances in the context of armed conflict, one can safely presume that they constitute a much smaller proportion of the missing and that the majority have been killed and their bodies hidden.

Discussion

Only recently have cultural anthropologists actively started to study violent human behavior in a modern context (e.g., Leyton 2005). In *Annihilating Difference: The Anthropology of Genocide*, Laban Hinton (2002:1) observed that, "Although anthropologists have long been at the forefront of advocating for the rights of indigenous people and have conducted rich analyses of violence, conflict, and warfare in substate and prestate societies, they have only recently (since the 1980s) begun to focus their attention intensively on political violence in complex state societies". Despite decades of being actively engaged in death-scene investigations, grave search and excavation, and skeletal analysis, forensic anthropologists have seldom explored beyond the realm of basic archaeological search and recovery techniques (Chapter 17) and osteological observations related to biological profile and trauma. This situation exists despite the four-field anthropology emphasis taught in most of North American universities, wherein forensic anthropology has been focused—both in research and practice. Only very recently have forensic anthropologists ventured into broader aspects of anthropological work such as material culture analysis and spatial analysis.

The modality of killings and body disposal in both peacetime and armed conflict contexts, changes due to evolving circumstances. Serial killers may become more brazen, careless, or adept with each subsequent kill. The Nazi Germans, the Nationalists during the Spanish Civil War, and the Ottoman soldiers during the Armenian Genocide demonstrated a learning process with respect to body disposal. Not only is it difficult to destroy a human body, it can be costly in terms of labor and other resources (such as bullets or fuel) that are often needed in large quantities to support the mechanized forces engaged in the war efforts.

Concerning the clandestinity of body disposal sites, the motivation to hide a body is driven largely by sociopolitical factors and will in turn influence taphonomic factors. Cases of domestic and serial homicides seem to show a concerted effort to hide, destroy, or at least to disassociate the offender from the victim's body, which is natural given the almost certain consequences for the offender who is caught and convicted. In the context of wide-scale killings of noncombatants during armed conflict, there is a range of behavior that reflects sociopolitical circumstances and mandates. In the Spanish Civil War, in areas of secure control and at the beginning of the war—when the war was still very much perceived as being a coup d'état—killings were often at or around established cemeteries, and attempts were made to burn bodies en masse. When publicity of Nationalist mass killings threatened to move international support toward the Republicans, Nationalist military orders were issued to dispose of bodies more discretely.

In Bosnia-Herzegovina, initial killings and mass body disposals (typically burials) were done only somewhat clandestinely, taking into consideration that United Nations and other foreign body agents were operating throughout the territory. Later, remarkable efforts were conducted to remove bodies from their primary burial places and rebury them in more clandestine secondary or even tertiary locations. Subsequently, in Kosovo, bodies were sometimes transported out of the territory and buried on military bases or other more secure locations in Serbia (Tuller et al. 2008). Thus, when one seeks the bodies of victims, one must take into account the objectives and constraints of the killers, given the sociopolitical context at the time of and subsequent to the killings.

An important conclusion reached by several authors who have studied individual and serial murderers is that their spatial decisions and movement related to their crimes and victim body disposal are not unlike that of other serial criminals (e.g., burglars and rapists). This observation lends weight to the feasibility of modeling the spatial behavior of those who are often popularly conceived of and portrayed by the media as unpredictable, incomprehensible psychopaths (e.g., Leyton 2005:327–330; Owen 2006). Research on body disposal patterns of homicide and serial homicide victims demonstrates that serial killers in different countries employ an "inherent logic" and are guided by rationality in their spatial choices. Studies of serial killers in several countries support the idea that behavior patterns are based on factors that transcend cultural and political boundaries.

In the study of the Spanish Civil War killings, it was posited that the near or actual impunity of killers led to their traveling only short distances (albeit at night) and killing victims along mostly primary roads. Likewise, impunity influenced how the Ottoman soldiers undertook the Armenian genocide—killing people using geographic features such as cliffs and drowning in rivers while rarely burying bodies—dictates the course of taphonomic processes and the type of evidence that can possibly be gathered. Meanwhile, data from studies on serial homicide and sexual homicide demonstrate that there is usually remarkably little difference in the distances traveled between victim-offender encounter site and body disposal site. The geometry across these very different types of killings suggests that the root of body disposal location is simply logical universal human behavior when faced with specific constraints and limited resources. The evidence of the taphonomic signature of *H. sapiens sapiens* suggests that the behavior of victim disposal across diverse contexts is logical and patterned. This conclusion should provoke further study of a topic that is certainly within the professional realm of anthropologists.

Notes

1. This revised version includes co-authors, Green and Seferian, who have conducted this line of research, albeit in different ways and with distinct perspectives, reinforcing the value of interdisciplinary research. Their inclusion was a deliberate decision by the sole author of the first version (Congram), who questions: *who* is an expert on the subject? We believe that the chapter is greatly improved by the inclusion of Pearl Seferian as an author. Thirty-two members of Pearl's family are missing from the Armenian genocide. She has dedicated a remarkable amount of time studying the subject and the missing and inspires by her seemingly infinite energy and dedication.
2. The author thanks Professor of Archaeology Jordi Estevez from the Universitat Autònoma de Barcelona for first suggesting this change in killing behavior by the Nationalist forces.
3. For the sake of this work, "criminal" removal of bodies is considered that which is not sanctioned or known by victim families and communities, and "noncriminal" is that organized or conducted by victim families and communities. It is acknowledged that either or both may be technical violations of criminal law or entirely legal, but moral rather than legalistic reasoning is used here to define these terms.

References

ABC TV Science (2000) *Unearthing Evil: Archaeology in the Cause of Justice*. Film. Electronic document, worldcat.org/title/unearthing-evil-archaeology-in-the-cause-of-justice/oclc/707972267, accessed 11 April 2021.

Aitken, C. G. G., T. Connolly, A. Gammerman, and G. Zhang (1994) *Statistical Analysis of the CATCHEM Data*. Unpublished manuscript, Police Research Group, Home Office, London.

Allen, P. (2010) *Katyn: Stalin's Massacre and the Triumph of Truth*. Northern Illinois University Press, DeKalb, IL.

Andresen, M. A., R. Frank, and M. Felson (2014) Age and distance to crime. *Criminology and Criminal Justice* 14(3):314–333.

AP (2003) Mass grave unearthed in Guatemala. Electronic document, http://www.guardian.co.uk/world/2003/sep/01/1, accessed 26 March 2021.

Armengou, M., and R. Belis (2004) *Las Fosas del Silencio*. Random House, Barcelona.

Auerbach, R. (1979) In the fields of Treblinka. In *The Death Camp Treblinka* ed. by A. Donat, pp. 19–74. Holocaust Library, New York.

Badcock, J. (2005) Saved by the war. *Index on Censorship* 2:68–71.

Bahamonde, A. (2005) *Un Año con Queipo de Llano*. Espuela de Plata, Sevilla, Spain.

Ball, H. (1999) *Prosecuting War Crimes and Genocide: The Twentieth-Century Experience*. University of Kansas, Lawrence, KA.

Baraybar, J. P. (2008) When DNA is not available, can we still identify people? Recommendations for best practice. *Journal of Forensic Sciences* 53(3):533–540.

Barcala, D. (2010) Mi padre está en la caja 198, en la cripta derecha. *Público*, 13th October. Electronic document, http://www.publico.es/espana/341266/mi-padre-esta-en-la-caja-198-en-la-cripta-derecha, accessed 26 March 2021.

Barcala, D. (2011) El Gobierno concluye que los cuerpos del Valle de los Caídos no son identificables. Electronic document, https://aricomemoriaaragonesa.wordpress.com/2011/05/04/el-gobierno-concluye-que-los-cuerpos-del-valle-de-los-caidos-no-son-identificables/, accessed 26 March 2021.

Baviano, J. M. (1980) El juicio contra el alcalde de Torremegía el recuerdo de los fusilamientos de 1936. *El País*, 22nd June. Electronic document, https://elpais.com/diario/1980/06/22/espana/330472803_850215.html, accessed 26 March 2021.

Bax, M. (1997) Mass graves, stagnating identification, and violence: A case study in the local sources of the war in Bosnia Hercegovina. *Anthropological Quarterly* 70(1):11–19.

BBC (1998) Murder in the Name of War—My Lai. Electronic document, http://news.bbc.co.uk/2/hi/asia-pacific/64344.stm, accessed 26 March 2021.

BBC (2005) Grim Account of Argentine Deaths. Electronic document, http://news.bbc.co.uk/2/hi/americas/4193341.stm, accessed 23 March 2021.

Becker, H. S. (1999) The Chicago School, so-called. *Qualitative Sociology* 22(1):3–12.

Beech, J. G. (2002) The differing development paths of Second World War concentration camps and the possibility of an application of a principle of equifinality. In *Matériel Culture; The Archaeology of Twentieth-Century Conflict* ed. by J. Schofield, W. G. Johnson, and C. M. Beck, pp. 199–207. Routledge, London.

Bennassar, B. (2005) *El Infierno Fuimos Nosotros*. Taurus, Madrid.

Berman, D. M. (2003) Calling the wandering souls: A journey through the heartland of ethnic cleansing. *War, Literature and the Arts* 15(1–2):267–282.

Bevan, D. (1994) *A Case to Answer: The Story of Australia's First European War Crimes Prosecution*. Wakefield, Kent Town, SA, Australia.

Bijak, J., and S. Lubman (2016) The disputed numbers: In search of the demographic basis for studies of Armenian population losses, 1915–1923. In *The Armenian Genocide Legacy* ed. by A Demirdjian, pp. 26–43. Palgrave Macmillan, London.

Bouckaert, P. (2003) The Mass Graves of Al-Mahawil: The Truth Uncovered. Human Rights Watch report, 15(5) (E), May 2003. Electronic document, https://www.hrw.org/reports/2003/iraq0503/iraq0503.pdf, accessed 26 March 2021.

Boudreaux, M. C., W. D. Lord, and R. L. Dutra (1999) Child abduction: Age-based analyses of offender, victim, and offense characteristics in 550 cases of alleged child disappearance. *Journal of Forensic Sciences* 44(3):539–553.

Bourke, J. (2000) *An Intimate History of Killing*. Granta Books, London.

Brown, K. M., and R. Keppel (2007) Child abduction murder: An analysis of the effect of time and distance separation between murder incident sites on solvability. *Journal of Forensic Sciences* 39(2):137–145.

Browning, C. (1998) *Ordinary Men; Reserve Police Battalion 101 and the Final Solution in Poland*. Harper Perennial, New York.

Bullock, H. A. (1955) Urban homicide in theory and fact. *Journal of Criminal Law, Criminology and Police Science* 45(5):565–575.

Canter, D. V., L. J. Alison, E. Alison, and N. Wentink (2004) The organized/disorganized typology of serial murder: Myth or model? *Psychology, Public Policy and Law* 10(3):293–320.

Castro, L. (2006) *Capital de la Cruzad: Burgos durante la Guerra Civil*. Crítica, Barcelona.

Comerford, C. V. (2021) A scoping review of serial homicide geographic mobility literature and four typologies. *Homicide Studies*. DOI: 10.1177/1088767921993506.

Congram, D. (2010) *Spatial Analysis and Predictive Modelling of Clandestine Graves from Rearguard Repression of the Spanish Civil War*. Ph.D. Dissertation, Simon Fraser University, Burnaby, BC, Canada.

Congram, D., A. Flavel, and K. Maeyama (2014) Ignorance is not bliss: Evidence of human rights violations from Civil War Spain. *Annals of Anthropological Practice* 38(1):43–64.

Congram, D., M. Kenyhercz, and A. G. Green (2017) Grave mapping in support of the search for missing persons in conflict contexts. *Forensic Science International* 278:260–268.

Congram, D., and J. Sterenberg (2009) Grave problems in Iraq. In *Handbook of Forensic Anthropology and Archaeology* ed. by S. Blau and D. H. Ubelaker, pp. 441–453. Left Coast Press, Walnut Creek, CA.

Cordner, S., and M. Tidball-Binz (2017) Humanitarian forensic action—Its origins and future. *Forensic Science International* 279:65–71.

Dabbs, G. R., M. Connor, and J. A. Bytheway (2016) Interobserver reliability of the total body score for quantifying human decomposition. *Journal of Forensic Sciences* 61(2):445–451.

Daly, M., and M. Wilson (1988) *Homicide*. Aldine de Gruyter, New York.

Daubert v. Merrell Dow Pharmaceuticals, Inc., 509 U.S. 579 (1993).

Dautartas, A., M. W. Kenyhercz, G. M. Vidoli, L. Meadows Jantz, A. Mundorff, and D. W. Steadman (2018) Differential decomposition among pig, rabbit, and human remains. *Journal of Forensic Sciences* 63(6):1673–1683.

Dern, H., R. Froend, U. Straub, J. Vick, and R. Witt (2004) *Geogrfisches Verhalten Fremder Taeter bei Sexuellen Gewaltdelikten* [Spatial Behaviour of Stranger Perpetrators in Sexually Violent Delinquency]. Bundeskriminalam, Wiesbaden, Germany.

Desbois, P. (2008) *The Holocaust by Bullets*, Palgrave MacMillan, New York.

Doretti, M., and C. C. Snow (2003) Forensic anthropology and human rights: The Argentine experience. In *Hard Evidence: Case Studies in Forensic Anthropology* ed. by D. W. Steadman, pp. 290–310. Prentice Hall, Upper Saddle River, NJ.

El Tiempo (2007) Por siete ríos corrió la sangre derramada, Las Fosas de los Paras. *El Tiempo* Tuesday 24 April 2007, pp. 1–9.

Espinosa, F. (2006) *Contra el Olvido: Historia y Memoria de la Guerra Civil*. Crítica, Barcelona.

Espinosa, F. (2007) *La Columna de la Muerte*. Crítica, Barcelona.

Espinosa, F. (2009) Informe sobre la represión franquista. In *La Gran Represióni* ed. by M. Núñez Díaz-Balart, pp. 433–469. Flor del Viento, Barcelona.

Etxeberría, F., and Q. Solé (2019) Fosas comunes de la guerra civil en el siglo XXI: Antecedentes, interdiscplinariedad y legislación. *Historia Contemporánea* 60(2):401–438.

Ferllini, R., and A. M. Croft (2009). The case of an Armenian mass grave. *Journal of Human Rights* 8(3):229–244.

Fernandez Muñoz, A., and D. Congram (2016) The evidentiary value of cultural objects from mass graves: Analysis, interpretation, and limitations. In *Missing Persons; Multidisciplinary Perspectives on the Disappeared* ed. by D. Congram, pp. 269–287. Canadian Scholars' Press, Toronto.

Ferrándiz, F. (2009) Fosas comunes, paisajes del terror. *Revista de Dialectología y Tradiciones Populares* 64(1):61–94.

Ferrándiz, F., and E. Silva Barrera (2016) From mass graves to human rights: The discovery of forced disappearances in contemporary Spain. In: *Missing Persons; Multidisciplinary Perspectives on the Disappeared* ed. by D. Congram, pp. 74–101. Canadian Scholars' Press, Toronto.

Fischer, B. B. (2005) The Katyn Controversy; Stalin's Killing Field. Studies in Intelligence Winter 1999-2000. Electronic document, https://www.cia.gov/static/5a3e46e77b3c417a15bcf927e7b049cc/Stalins-Killing-Field.pdf, accessed 26 March 2021.

FitzGibbon, L. (1971) *Katyn*. Tom Stacey, London.

FitzGibbon, L. (1975) *Unpitied and Unknown; Katyn… Bologoye… Dergachi*. Bachman and Turner, London.

Flavel, A., and C. Barker (2009) Forensic anthropology and archaeology in Guatemala. In *Handbook of Forensic Anthropology and Archaeology* ed. by S. Blau and D. H. Ubelaker, pp. 426–440. Left Coast Press, Walnut Creek, CA.

Fleischman, J. M. (2016) Working with the remains in Cambodia: Skeletal analysis and human rights after atrocity. *Genocide Studies and Prevention* 10(2):121–130.

Gabor, T., and E. Gottheil (1984) Offender characteristics and spatial mobility: An empirical study and some policy implications. *Canadian Journal of Criminology* 23(26):267–281.

Gibson, I. (1973) *The Death of Lorca*. W. H. Allen, London.

Godwin, M., and D. Canter (1997) Encounter and death: The spatial behavior of US serial killers. *Policing: An International Journal of Police Strategy and Management* 20(1):24–38.

Gojanović, M. D., and D. Sutlović (2007) Skeletal remains from World War II mass grave: From discovery to identification. *Croatian Medical Journal* 48(4):520–527.

Gómez, L., and N. Junquera (2008) Dónde acabaron? *El País, Domingo*, 14 September 2008.

Gómez-López, A. M., and A. Patiño Umaña (2007) Who is missing? Problems in the application of archaeology and anthropology in Colombia's conflict. In *Forensic Archaeology and Human Rights Violations* ed. by R. Ferllini, pp. 170–204. Charles C Thomas, Springfield, IL.

Graham, H. (2005) *The Spanish Civil War*. Oxford University Press, Oxford.

Haglund, W. D., M. Connor, and D. D. Scott (2001) The archaeology of contemporary mass graves. *Historical Archaeology* 35(1):57–69.

Häkkänen, H., K. Hurme, and M. Liukkonen (2007) Distance patterns and disposal sites in rural area homicides committed in Finland. *Journal of Investigative Psychology and Offender Profiling* 4(3):181–197.

Hanfland, K. A., R. D. Keppel, and J. G. Weis (1997) *Case Management for Missing Children Homicide Investigation*. Attorney General of Washington and U.S. Department of Justice Office of Juvenile Justice and Delinquency Prevention, Olympia, WA.

Herrero Balsa, G., and A. Hernández García (1982) *La Represión en Soria Durante la Guerra Civil*. Herrero Balsa and Hernández García, Soria, Spain.

Herreros, F., and H. Criado (2009) Pre-emptive or arbitrary: Two forms of lethal violence in a civil war. *Journal of Conflict Resolution* 53(3):419.

Hess, P. (2004) Evidence to be Unearthed from Mass Ggraves. Electronic document, http://www.washingtontimes.com/news/2004/jan/6/20040106-093959-2372r/, accessed 26 March 2021.

Hirz, R. (1999) *Republic of Austria, Federal Ministry of the Interior, Kosovo Crime Scene Team, Crimes Scene: XXI*. International Criminal Tribunal for the former Yugoslavia, Translation 03010876.

Holland, T. D., B. E. Anderson, and R. W. Mann (2002) Human variables in the postmortem alteration of human bone: Examples from U.S. war casualties. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 263–274. CRC Press, Boca Raton, FL.

Human Rights Watch (1997) Bosnia and Hercegovina: The Unindicted; Reaping the Rewards of Ethnic Cleansing. Electronic document, https://www.hrw.org/reports/1997/bosnia2/, accessed 26 March 2021.

Human Rights Watch (2004) Iraq: State of the Evidence. *Human Rights Watch Report* 16(7):1–41.

ICMP (2004) Summary Report on the Forensic Monitoring Activities Relating to the Excavation and Recovery of Human Remains from Several Related Features Located at Batajnica, Serbia and Montenegro, August to December 2002. Electronic document, https://www.icmp.int/wp-content/uploads/2014/08/icmp-fsd-16-04-2-doc.pdf, accessed 26 March 2021.

ICTY (2003) International Criminal Tribunal for the Prosecution of Persons Responsible for Serious Violations of International Law Committed in the Territory of the Former Yugoslavia Since 1991, Witness Statement, document X0169239. Electronic document, http://icr.icty.org, accessed 21 April 2021.

Indra, L., K. Straub, W. Schulz, R. Balsam, W. Ockert, S. Nowack, and A. Laue (2020) Missing, not forgotten. The German Association for the Recovery of the Fallen in Eastern Europe (VBGO e.V.). *Forensic Science International* 316:110473. DOI: 10.1016/j.forsciint.2020.110473.

Jackson, G. (1965) *The Spanish Republic and the Civil War*. Princeton University Press, Princeton, NJ.

Jasinski, M., K. Spradley, and M. Kaplan (2021) Tales of Small Things: Personal Belongings of Undocumented Migrants in Texas. Poster. American Academy of Forensic Sciences. Electronic document, academia.edu/44965388/Tales_of_Small_Things_Personal_Belongings_of_Undocumented_Migrants_in_Texas, accessed 11 April 2021.

Jennings, S. (2009) Kosovo Victims Relatives Testify about Mass Graves. Electronic document, https://iwpr.net/global-voices/kosovo-victims-relatives-testify-about-mass-graves, accessed 26 March 2021.

Jugo, A., and S. Wastell (2015) Disassembling the pieces, reassembling the social. The forensic and political lives of secondary mass graves in Bosnia and Herzegovina. In *Human Remains and Identification: Mass Violence, Genocide and the "Forensic Turn"* ed. by E. Anstett and J. M. Dreyfus, pp. 142–174. Manchester University Press, Manchester, UK.

Kalyvas, S. N. (2006) *The Logic of Violence in Civil War*. Yale University Press, New Haven, CT.

Kalyvas, S. N. (2003) The ontology of political violence: Action and identity in civil wars. *Perspectives on Politics* 1:475–494.

Kamenetsky, I. (ed.) (1989) *The Tragedy of Vinnytsia*. Ukrainian Historical Association, Toronto.

Keppel, R., and J. Weis (1993) Time and distance as solvability factors in murder cases. *Journal of Forensic Sciences* 39(2):386–401.

Kévorkian, R. H. (2014) Earth, fire, water: Or how to make the Armenian corpses disappear. In *Destruction and Human Remains: Disposal and Concealment in Genocide and Mass Violence* ed. by E. Anstett and J. M. Dreyfus, pp. 89–116. Manchester University Press, Manchester, UK.

Komar, D. A., and S. Lathrop (2008) The use of material culture to establish the ethnic identity of victims in genocide investigations: A validation study from the American Southwest. *Journal of Forensic Sciences* 53(5):1035–1039.

Kovras, I. (2012) De-linkage processes and grassroots movements in transitional justice. *Cooperation and Conflict* 47(1):88–105.

Kraemer, G. W., W. D. Lord, and K. Heilbrun (2004) Comparing single and serial homicide offenses. *Behavioral Sciences and the Law* 22(3):325–343.

Laban Hinton, D. (2002) The dark side of modernity. In *Annihilating Difference: The Anthropology of Genocide* ed. by A. L. Hinton, pp. 1–39. University of California Press, Berkeley, CA.

Lecomte, D., and W. Vorhauer (1999) *French Forensic Mission Kosovo—Summer 1999; Site Report, Cirez Site 2nd and 3rd July 1999*. International Criminal Tribunal for the former Yugoslavia, court document 03035631 (K017-6651-K017-6756). Electronic document, http://icr.icty.org, accessed 21 April 2021.

Lee, S. J., and J. Park (2019) Body transportation after homicides: Offender and offense characteristics. *Journal of Forensic Sciences* 64(4):1092–1095.

Leyton, E. (2005) *Hunting Humans*. McClelland and Stewart, Toronto.

Listi, G. A., M. H. Manhein, and M. Leitner (2007) Use of the global positioning system in the field recovery of scattered human remains. *Journal of Forensic Sciences* 52(1):11–15.

Lord, W. D., M. C. Boudreaux, J. P. Jarvis, J. Waldvogel, and H. Weeks (2002) Comparative patterns in life course victimization: Competition, social rivalry, and predatory tactics in child homicide in the United States. *Homicide Studies* 6(4):325–347.

Lundrigan, S. (2016) A review of research into the spatial behaviour of murderers and implications for investigations involving missing murder victims. In: *Missing Persons; Multidisciplinary Perspectives on the Disappeared* ed. by D. Congram, pp. 184–206. Canadian Scholars' Press, Toronto.

Lundrigan, S., and D. Canter (2001a) Spatial patterns of serial murder: An analysis of disposal site location choice. *Behavioral Sciences and the Law* 19(4):595–610.

Lundrigan, S., and D. Canter (2001b) A multivariate analysis of serial murderers disposal site location choice. *Journal of Environmental Psychology* 21(4):423–432.

Manhein, M. H., G. A. Listi, and M. Leitner (2006) The application of geographic information systems and spatial analysis to assess dumped and subsequently scattered human remains. *Journal of Forensic Sciences* 51(3):469–474.

Manning, D. (2000) *Srebrenica Investigation; Summary of Forensic Evidence—Execution Points and Mass Graves*. United Nations International Criminal Tribunal for the former Yugoslavia. Office of the Prosecutor Exhibit 140. Document 00950901. Electronic document, http://icr.icty.org, accessed 21 April 2021.

Mant, A. K. (1987) Knowledge acquired from post-war exhumations. In *Death, Decay and Reconstruction: Approaches to Archaeology and Forensic Science* ed. by A. Boddington, A. N. Garland, and R. C. Janaway. Manchester University Press, Manchester, UK.

Mark, J. (2010) What remains? Anti-communism, forensic archaeology, and the retelling of the national past in Lithuania and Romania. *Past and Present* 206(Sup. 5):276–300.

Márquez-Grant, D., and D. Errickson (2021) The legislation, search, recovery, identification and repatriation of conflict casualties worldwide: Introducing the WWI and WWII Special Issue. *Forensic Science International* 320:110716. DOI: 10.1016/j.forsciint.2021.110716.

Martín Barrio, A., M. de los Angeles Sampedro Talabán, and M. J. Velasco Marcos (1988) Dos formas de violencia durante la guerra civil. La represión en Salamanca y la Resistencia armada en Zamora. In *Historia y Memoria de la Guerra Civil* (vol. 2) ed. by J. Aróstegui, pp. 367–438. Junta de Castilla y León, Valladolid, Spain.

Maver, D. (2004) Historical Overview: The Ethnic Wars Phenomena towards the End of the Second Millennium and Some Problems of Investigation of War Crimes. Electronic document, https://www.ojp.gov/pdffiles1/nij/Mesko/208007.pdf, accessed 26 March 2021.

Morris, B., and D. Ze'evi (2019) *The Thirty-Year Genocide: Turkey's Destruction of its Christian Minorities, 1894–1924*. Harvard University Press, Boston.

Morton, R. J., and W. D. Lord (2002) Detection and recovery of abducted and murdered children: Behavioral and taphonomic influences. In *Advances in Forensic Taphonomy: Method, Theory and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 151–171. CRC Press, Boca Raton, FL.

Moyssi, N., M. Ktori, and U. Vehit (2016) Forensic management of artifacts in human identification: The experience of the Committee on Missing Persons in Cyprus. *Journal of Forensic Identification* 66(3):209–231.

Nethery, K. (2002) *Non-Familial Abductions that End in Homicide: An Analysis of the Distance Patterns and Disposal Sites*. M.A. Thesis, Simon Fraser University, Burnaby, BC, Canada.

Olson, A. P. (1966) A mass secondary burial from Northern Arizona. *American Antiquity* 31(6):822–876.

OSCE (1999) Violation of the right to life. In *Kosovo/Kosova; as Seen, as Told*. Organization for Security and Co-operation in Europe, Office for Democratic Institutions and Human Rights. Electronic document, https://www.osce.org/files/f/documents/d/d/17772.pdf, accessed 26 March 2021.

Owen, D. (2006) Hubris and nemesis in heads of government. *Journal of the Royal Society of Medicine* 99(11):548–551.

Oxford English Dictionary (2021) Online Edition. Electronic document, http://www.oed.com/, accessed 26 March 2021.

Palo, J. U., M. Hedman, N. Söderholm, and A. Sajantila (2007) Repatriation and identification of Finnish World War II Soldiers. *Croatian Medical Journal* 48(4):528–535.

Petrou, M. (2005) Sex, spies and Bethune's secret. *Maclean's* 118(43):46–52.

Pons Prades, E. (2006) *Las Escuadras de la Muerte*. Flor del Viento Ediciones, Barcelona.

Prada Rodríguez, J. (2006) *De la Agitación Republicana a la Represión Franquista. Ourense 1934–1939*. Ariel, Madrid

Prieto, J. L., C. Magaña, and D. Ubelaker (2004) Interpretation of postmortem change in cadavers in Spain. *Journal of Forensic Sciences* 49(5):1–6.

Rand, A. (1986) Mobility triangles. In *Metropolitan Crime Patterns* ed. by R. M. Figlio, S. Hakim, and G. F. Rengert, pp. 117–126. Criminal Justice Press, Monsey, NY.

Raszeja, S., and E. Chróścielewski (1994) Medicolegal reconstruction of the Katyn forest massacre. *Forensic Science International* 68:1–6.

Recknagel, C. (2003) Iraqis open Saddam Hussein's mass graves, demand justice (Part 1). *Radio Free Europe*, July 7. Electronic document, http://www.rferl.org/content/article/1103735.html, accessed 26 March 2021.

Reddick, A. (2006) *The Use of Spatial Techniques in the Location and Excavation of Contemporary Mass Graves*. M.Phil. Thesis, University of Birmingham, Birmingham, UK.

Rees, L. (2005) *Auschwitz: The Nazis and the "Final Solution"*. BBC Books, London.

Reig Tapia, A. (1979) En torno al estudio de la represión franquista. *Tiempo de Historia* 58(9):4–23.

Reig Tapia, A. (2006) Represión y esfuerzo humanitarios. In *La Guerra Civil Española* ed. by E. Malefakis, pp. 521–552. Taurus, Madrid.

Rengert, G. F., A. R. Piquero, and P. R. Jones (1999) Distance decay reexamined. *Criminology* 37(2):427–446.

Ressler, R. K., A. W. Burgess, J. E. Douglas, C. R. Hartman, and R. B. D'Agostino (1986) Sexual killers and their victims: Identifying patterns through crime scene analysis. *Journal of Interpersonal Violence* 1(3):288–308.

Rhodes, R. (2002) *Masters of Death: The SS-Einsatzgruppen and the Invention of the Holocaust*. Random House, New York.

Richards, M. (2007) Los límites de la cuantificación: Represión franquista y la metodología histórica. *Hispania Nova 7*. Electronic document, http://hispanianova.rediris.es/7/dossier/07d015.pdf, accessed 26 March 2021.

Rilova Pérez, I. (2001) *Guerra Civil y Violencia Política en Burgos (1936–1943)*. Editorial Dorsales, Burgos, Spain.

Rodrigo, J. (2008) *Hasta la Raíz*. Editorial Alianza, Madrid.

Rosenblatt, A. (2015) *Digging for the Disappeared*. Stanford University Press, Palo Alto, CA.

Rossmo, D. K. (1995) *Geographic Profiling: Target Patterns of Serial Murderers*. Ph.D. Dissertation, Simon Fraser University, Burnaby, BC, Canada.

Rossmo, D. K. (2000) *Geographic Profiling*. CRC Press, Boca Raton, FL.

Ruíz, J. (2009) Seventy years on: Historians and repression during and after the Spanish Civil War. *Journal of Contemporary History* 44(3):449–472.

Safarik, M. E., J. P. Jarvis, and K. E. Nussbaum (2000) Elderly female serial sexual homicide: A limited empirical test of criminal investigative analysis. *Homicide Studies* 4(3):294–307.

Salfati, C. G., and A. L. Bateman (2005) Serial homicide: An investigation of behavioural consistency. *Journal of Investigative Psychology and Offender Profiling* 2(2):121–144.

Santtila, P., M. Laukkanen, A. Zappalà, and D. Bosco (2008) Distance travelled and offence characteristics in homicide, rape, and robbery against business. *Legal and Criminological Psychology* 13(2):345–356.

Santtila, P., M. Laukkanen, and A. Zappalà (2007) Crime behaviours and distance travelled in homicides and rapes. *Journal of Investigative Psychology and Offender Profiling* 4(1):1–15.

Schofield, J., W. G. Johnson, and C. M. Beck (2002) *Matériel Culture: The Archaeology of Twentieth-Century Conflict*. Routledge, London.

Seferian, P. (2015) *Resistance: A Diary of the Armenian Genocide 1915–1922*. Tavrez Publishing, London, Canada.

Semerdjian, E. (2018) Bone memory: The necrogeography of the Armenian genocide in Dayr al-Zur, Syria. *Human Remains and Violence* 4(1):56–75.

Shaw, S. (1998) *Applying Environmental Psychology and Criminology: The Relationship between Crime Site Locations within Offences of Murder*. Undergraduate Thesis, University of Plymouth, UK.

Silva, E., and S. Macías (2003) *Las Fosas de Franco*. Temas de Hoy, Madrid.

Simmons, T. (2002) Taphonomy of a karstic cave execution site at Hrgar, Bosnia-Herzegovina. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 263–275. CRC Press, Boca Raton, FL.

Skinner, M. (2007) Hapless in Afghanistan: Forensic archaeology in a political maelstrom. In *Forensic Archaeology and Human Rights Violations* ed. by R. Ferllini, pp. 233–265. Charles C Thomas, Springfield, IL.

Skinner, M., D. Alempijevic, and M. Djuric-Srejic (2003) Guidelines for international forensic bio-archaeology monitors of mass grave exhumations. *Forensic Science International* 134:81–92.

Skinner, M., A. Fernández, and D. Congram (2009) Material culture analysis in forensic cases: A call for formal recognition by forensic anthropologists. *Proceedings of the American Academy of Forensic Sciences* 15:336–337.

Skinner, M., and E. Jessee (2005) A typology of mass grave and mass grave-related sites. *Forensic Science International* 152:55–59.

Skinner, M., and R. Lazenby (1983) *Found! Human Remains: A Field Manual for the Recovery of the Recent Human Skeleton*. Archaeology Press, Simon Fraser University, Burnaby, BC, Canada.

Skinner, M. F., H. P. York, and M. A. Connor (2002) Postburial disturbance of graves in Bosnia-Herzegovina. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 293–307. CRC Press, Boca Raton, FL.

Snook, B., R. M. Cullen, A. Mokros, and S. Harbort (2005) Serial murderers' spatial decisions: Factors that influence crime location choice. *Journal of Investigative Psychology and Offender Profiling* 2(3):147–164.

Steadman, D. W., and W. D. Haglund (2005) The scope of anthropological contributions to human rights investigations. *Journal of Forensic Sciences* 50(1):23–30.

Sturdy Colls, C. (2015) *Holocaust Archaeologies: Approaches and Future Directions*. Springer, New York.

Sui, D. Z. (2009) Tobler's first law of geography: A big idea for a small world? *Annals of the Association of American Geographers* 94(2):269–277.

Susa, E. (2007) Forensic anthropology in Hungary. In *Forensic Anthropology: Case Studies from Europe* ed. by M. Brickley and R. Ferllini, pp. 203–215. Charles C Thomas, Springfield, IL.

Szleszkowski, L., A. Thannhauser, K. Szwagrzyk, and T. Jurek (2015) The possibility of establishing causes of death on the basis of the exhumed remains of prisoners executed during the communist regime in Poland: The exhumations at Powazki Military Cemetery in Warsaw. *International Journal of Legal Medicine* 129(4):801–806.

Torres, R. (2002) *Desaparecidos de la Guerra de España (1936–?)*. La Esfera de los Libros, Madrid.

Tremlett, G. (2005) Argentinean Jailed for Throwing Prisoners from Plane. Electronic document, http://www.guardian.co.uk/world/2005/apr/20/argentina.gilestremlett, 26 March 2021.

Tuller, H. (2012) Mass graves and human rights: Latest developments, methods and lessons learned. In *A Companion to Forensic Anthropology* ed. by D. C. Dirkmaat. Wiley-Blackwell, Hoboken, NJ.

Tuller, H., U. Hofmeister, and S. Daley (2008) Spatial analysis and mass grave mapping data to assist in the reassociation of disarticulated and commingled remains. In *Recovery, Analysis, and Identification of Commingled Remains* ed. by B. J. Adams and J. E. Byrd, pp. 7–30. Humana Press, Totowa, NJ.

Van Patten, I. T., and P. Q. Delhauer (2007) Sexual homicide: A spatial analysis of 25 years of deaths in Los Angeles. *Journal of Forensic Sciences* 52(5):1129–1141.

Vass, A. A. (2011) The elusive universal post-mortem interval formula. *Forensic Science International* 201:34–40.

Verna, E., C. Costedoat, A. Stevanovitch, F. Adam, Y. Desfossés, A. Jacques, and M. Signoli (2020) French soldiers who died during both World Wars: From recovery to repatriation. *Forensic Science International* 316:110484. DOI: 10.1016/j.forsciint.2020.110484.

Vilaplana, R. (1977) *Doy Fe* (3rd ed.). Epidauro, Barcelona.

Walston, J. (1997) History and memory of the Italian concentration camps. *The Historical Journal* 40(1):169–183.

Warren, M. W., and W. R. Maples (1997) The anthropometry of contemporary commercial cremation. *Journal of Forensic Sciences* 42(3):417–423.

Weiss-Wendt, A. (2003) Extermination of the Gypsies in Estonia during World War II: Popular images and official policies. *Holocaust and Genocide Studies* 17(1):31–61.

Wessling, R., and L. Loe (2011) The Fromelles project—The recovery and identification of British and Australian WWI soldiers from mass graves in Northern France. *Proceedings of the American Academy of Forensic Sciences* 17:369.

Wolentarska-Ochman, E. (2006) Collective remembrance in Jedwabne: Unsettled memory of World War II in postcommunist Poland. *History and Memory* 18(1):152–178.

World Bank (2021) World Development Indicators. Electronic document, https://ourworldindata.org/grapher/population-density, accessed 11 April 2021.

Wright, R. (1995) Investigating war crimes: The archaeological evidence. *The Sydney Papers* 7(3):39–44.

Wright, R. (2010) Where are the bodies? In the ground. *Public Historian* 32(1):96–107.

Wright, R., I. Hanson, and J. Sterenberg (2005) The archaeology of mass graves. In *Forensic Archaeology: Advances in Theory and Practice* ed. by J. Hunter and M. Cox, pp. 137–158. Routledge, London.

Zavala, J. M. (2006) *Los Horrores de la Guerra Civil*. DeBosillo, Madrid.

11

Subaerial Weathering and Other Terrestrial Surface Taphonomic Processes

JAMES T. POKINES
CHRISTINE A. SPIEGEL

Contents

> DOT: George, why is it you always get to sit in the shade
> While I have to stand in the sun?
>
> —**Stephen Sondheim**
> *Sunday in the Park with George*

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Introduction

Subaerial bone weathering can be described in lay terms as grossly similar to what happens to exterior house paint: it bleaches, loses moisture, cracks, and flakes due to exposure to solar radiation, temperature fluctuations, precipitation, and sometimes from chemical processes and is spalled off in thin fragments (Figure 11.1). While the chemical (Nielsen-Marsh et al. 2000) and physical processes undergone by weathering bones are very different than paint, the end result is a bone that is fragmenting apart to become part of the lithosphere, completing its taphonomic cycle. The relevance of osseous weathering to forensic analyses is twofold. First, it is necessary to distinguish this type of taphonomic alteration from other sources, including other processes that bleach and/or crack bone, in order to understand the context from where the bone came. This includes taphonomic alterations that might link a bone to a certain depositional setting, such as weathered remains from a surface deposit, which later get moved to a new location. Similarly, the movement of a bone from its original position while remaining in the same general location is often discernible from its weathering pattern. Second, and of most importance in forensic anthropology, is the information that osseous weathering can give regarding the postmortem interval (PMI). Estimation of the PMI in the middle range between where decomposition and entomological studies leave off (typically less than one year) and radiocarbon dating/bomb curve analysis begins. Forensic anthropologists have few viable options within this interval

Figure 11.1 Detail of a weathered nonhuman long bone surface. Note the delamination. The scale is in cm.

(Beary 2005) and often must rely upon artifactual evidence accompanying remains (clothing or other personal objects), broad taphonomic patterns indicating a lack of forensic relevance (Chapter 5), or related analyses such as the development of annual rings in trees in direct association with remains (Pokines 2018; Willey and Heilman 1987). Weathering analysis also has the potential for misuse where temporal standards developed in different environments are applied uncritically to estimate the PMI (Lyman 1994; Lyman and Fox 1989, 1997).

The effects of differing environment (including temperate deciduous forest, semiarid equatorial savanna, or tundra) and microhabitat within that environment (i.e., patches of tree, brush, wetland, or grass cover within a temperate deciduous forest) upon the rates of osseous weathering have been little researched in any world region (Andrews and Cook 1985; Cutler et al. 1999; Hill 1976; Janjua and Rogers 2008; Miller 2009; Pokines 2009; Purdy and Clark 1987; Ross and Cunningham 2011; Tappen 1969, 1976, 1994; Ubelaker and Sperber 1988; Western and Behrensmeyer 2009; White and Hannus 1983). This gap in our knowledge is likely due to the time needed to gather observations of weathering changes over a meaningful time span (Behrensmeyer 1978; Behrensmeyer and Miller 2012; Toots 1965; Western and Behrensmeyer 2009), or the need to have bones of known depositional age with which to commence a study (Miller 2009). In addition, a large sample size in a natural setting, where the same skeletal elements can be identified and their individual changes recorded year after year, must be utilized. Due to potential seasonality effects, one also must know the timing of deposition within a given year. Only long-term research projects spanning decades can answer these questions, combined where possible with naturalistic observations of bones deposited at known times in the past (Miller 2009).

Subaerial weathering also makes bones in some cases more susceptible to other kinds of taphonomic alteration. Most importantly, many species of rodent preferentially gnaw on dry, weathered bone. These include many species of porcupines, large rodents with wide ranges throughout the world that can damage bones greatly in order to wear their incisors and obtain mineral salts from bone (Brain 1980, 1981; Kerbis Peterhans 1990; Roze 2009; Chapter 9). The breakdown of the bone surface also makes it susceptible to subsequent rounding and wear when introduced into an abrasive fluvial environment (Fernández-Jalvo and Andrews 2003), making the loss of the surface layers more rapid. The loss of surface features from both of these processes limits the biological information that can be derived from a bone, including element, species, development, and evidence of perimortem trauma. Dry, weathered bone also is altered differently when burned than is fresh, green bone (Buikstra and Goldstein 1973; Buikstra and Ubelaker 1994), providing important clues regarding the timing of postmortem thermal alteration. Micozzi (1991) notes that the end process of weathering may delete the less robust bones from a surface assemblage first, changing the relative proportions of skeletal elements surviving for analysis. Drying and loss of organic component accompanying the weathering process also make bones of less interest to large scavengers, decreasing the likelihood for further gnawing and dispersal by these taxa (Faith and Behrensmeyer 2006). Surface deposition also makes bones far more likely to undergo multiple other taphonomic processes, including algal and other biological interactions (see "Other Effects of Surface Exposure" section, below). Subaerial weathering is one part of an interlocking pattern of taphonomic changes that skeletal remains may undergo.

Processes of Subaerial Weathering

Bone Properties

The exact mechanisms of bone weathering have been understudied experimentally, but the gross physical processes involve the loss of organic content, loss of moisture, bleaching of the surface layers, and cracking (Beary 2005; Behrensmeyer 1978; Behrensmeyer and Miller 2012; Brain 1967; Cutler et al. 1999; Miller 1975). In materials science, *fatigue* is the localized, cumulative structural damage caused by repeated loading and unloading of an object that leads to cracking, fracture, and failure. Schütz (1996) provides a detailed history of the study of fatigue, emphasizing the German contribution made during the mid-1900s, and these same principles from engineering may be applied to organic supportive tissues. Living bone is subjected to constant stresses and may fail cumulatively under these conditions (forming a stress fracture) or more rapidly under more extreme loading (Cox and Yang 2007; Doblaré et al. 2004; Galloway 1999; Tomar 2009), but living bone can repair damage and reshape itself in response to repeated stress (Wolff's law). Dead bone no longer has the capacity for self-repair, and cumulative fatigue through multiple environmental stresses leads to crack propagation and its gradual flaking apart in more advanced stages.

Since the collagen fibers in living/fresh bone limit crack propagation through the mineral (largely hydroxyapatite) matrix, any collagen loss or breakdown also will reduce a bone's ability to withstand cracking. Using SEM imaging, Thurner et al. (2007) noted that bone fails by the delamination and separation of mineralized collagen fibrils, which results in the whitening of the bone. The collagen component is also largely responsible for the ability of bone to withstand tensile forces (Doblaré et al. 2004), so any taphonomic process that expands bone is more likely to cause cracking when the collagen component is degraded. Similarly, partial dissolution of the mineral component also will weaken bone and increase the ease with which other taphonomic processes can cause cracking and flaking. This process is paralleled in living persons with osteoporosis, whose bones break far more easily (and often just from muscle contraction without any corresponding blunt force trauma) as the mineral component decreases (Doblaré et al. 2004; McGee et al. 2007).

Patterns of Physical Degradation to Osseous Remains

Miller (1975) and Behrensmeyer (1978) first laid out stages of osseous weathering for large mammals, the latter describing six *weathering stages* (WS 0 through WS 5) based on the progressive pattern of linear cracking and flaking of the cortical surface, followed by formation of a rough fibrous texture, and eventual loss of bone structure. (These stages with accompanying photographs are reproduced in their entirety in Buikstra and Ubelaker [1994].) These proceed as outlined in Table 11.1. When determining which weathering stage should be assigned, Behrensmeyer (1978) indicated that the most advanced stage covering an area larger than 1 cm^2 should be recorded, avoiding areas of physical damage, and all observers must agree concerning the stage before it is recorded. While the scale should not be applied to teeth or small vertebrate skeletons, it has been applied to antler successfully (Miller et al. 2013). This progressive pattern of cracking and flaking is the basis for determining weathering stages and is broadly indicative of the period of surface exposure (Behrensmeyer 1978). While the rate of weathering is highly dependent upon climate and microenvironment, the stages of weathering seem to follow the same pathway

Table 11.1 Summary of Weathering Stages as Defined by Behrensmeyer (1978)

WS	Bone Condition	Soft Tissue
0	Bone surface shows no sign of cracking or flaking due to weathering.	Usually bone is still greasy, marrow cavities contain tissue, skin, and muscle/ligament may cover part or all of the bone surface.
1	Bone shows cracking, normally parallel to the fiber structure (e.g., longitudinal in long bones). Articular surfaces may show mosaic cracking of covering tissue as well as in the bone itself.	Fat, skin, and other tissue may or may not be present.
2	Outermost concentric thin layers of bone show flaking, usually associated with cracks, in that the bone edges along the cracks tend to separate and flake first. Long thin flakes, with one or more sides still attached to the bone, are common in the initial part of Stage 2. Deeper and more extensive flaking follows, until most of the outermost bone is gone. Crack edges are usually angular in cross-section.	Remnants of ligaments, cartilage, and skin may be present.
3	Bone surface is characterized by patches of rough, homogeneously weathered compact bone, resulting in a fibrous texture. In these patches, all the external, concentrically layered bone has been removed. Gradually the patches extend to cover the entire bone surface. Weathering does not penetrate deeper than 1.0–1.5 mm at this stage, and bone fibers are still firmly attached to each other. Crack edges usually are rounded in cross-section.	Tissue rarely present at this stage [or beyond].
4	The bone surface is coarsely fibrous and rough in texture; large and small splinters occur and may be loose enough to fall away from the bone when it is moved. Weathering penetrates into inner cavities. Cracks are open and have splintered or rounded edges.	
5	Bone is falling apart in situ, with large splinters lying around what remains of the whole, which is fragile and easily broken by moving. Original bone shape may be difficult to determine. Cancellous bone usually exposed, when present, and may outlast all traces of the former more compact, outer parts of the bones.	

Source: Behrensmeyer (1978); used with permission, Cambridge University Press.

as the pattern described earlier, regardless of environmental conditions (Behrensmeyer and Miller 2012; Buikstra and Ubelaker 1994; Madgwick and Mulville 2012; Miller 2009; Tappen 1994).

Weathering is characterized by both cracking, where splits penetrate inward, and delamination, where splits occur circumferentially and layers of bone peel away from the remainder, slowly reducing overall bone size and integrity. More general flaking can occur where irregular fragments spall off. Bone cracking due to weathering normally runs parallel to the orientation of the osteons, following the *split-line orientation* of a bone (Buckland-Wright 1977; Christensen et al. 2019; Tappen 1969, 1976; Tappen and Peske 1970). In practical terms, cracking tends to proceed parallel to the long axes of the ribs, long bones, metapodials, and other bones with a long, narrow structure (Hill 1976) (Figure 11.2). On other irregularly shaped elements such as vertebrae (Figure 11.3), the direction of cracking

Figure 11.2 Weathered caprine rib, WS 3. Note how the cracks orient parallel to the shaft of the rib, with patches of delamination exposing a rough, fibrous texture and some deeper cracking.

Figure 11.3 Weathered (WS 3) caprine vertebra. Note how the cracks orient parallel to the major structures of the bone and note the patches of delamination exposing the rough, fibrous texture.

follows the less-linear overall osteon orientation, which must orient in more than one direction to follow multiple directions of stress. Weathering cracks of these elements therefore tend to be more irregular.

The microscopic structure of bone is also key to understanding how it weathers, and how variations in the major structural type of bone may affect how weathering proceeds. Plexiform (or fibrolamellar) bone is found in very young humans but is a common microscopic structural type in large nonhuman mammals due to their rapid growth requirements (Hillier and Bell 2007; Morris 2007; Weiner and Wagner 1998) and short lifespans in the wild or under most domesticated systems of butchery timing, where subadults are normally culled. These include many of the species of quadrupeds (primarily Bovidae) whose remains were analyzed by Behrensmeyer (1978) in her original systemization of weathering stages. Plexiform bone has a regular, “brick like” structure and is laid down in radial bands, which in bovids are approximately 200 µm thick (Currey 2002:18). The microscopic plexiform structure consists of layers of parallel-fiber woven bone, which is laid down rapidly, with lamellar bone more slowly filling in the cavities in the woven structure. This structure may get transformed gradually into lamellar bone as the animal ages, including primary and secondary osteon formation (Stover et al. 1992). In the lamellar bone of adult humans, the osteonal structure does not fit the regular osteonal banding of plexiform bone, and the constant remodeling of secondary osteons rewrites/replaces the primary osteonal structure (Mulhern and Ubelaker 2001). No osteonal banding is present, so spalling of lamellar bone surfaces due to weathering (apart from the surface layer) is likely to be much more irregular than that in plexiform bone, although the cracking of the surface of lamellar bone tends to parallel the underlying osteonal structure (Buckland-Wright 1977; Tappen 1969, 1976; Tappen and Peske 1970). Models of bone weathering derived from nonhuman mammal species therefore may not be precisely applicable to adult human remains, but a great deal of long-term research using human bones in controlled settings in direct comparison with nonhuman bones is required to answer this question.

Examples of the slow breakdown of bone by weathering are shown in Figures 11.2 through 11.9, which also illustrate the effects that the presence of plexiform bone, with its regular layered structure, has upon surface flaking/spalling. Note that while the surface of the bone is highly cracked and beginning to spall (Figure 11.4), the interior cortical structure is undamaged and highly intact. Subsequent removal of the outer weathered surface of this bone (such as through sand abrasion in a marine coastal environment) would leave little trace that the bone had been weathered previously (Fernández-Jalvo and Andrews 2003). Bone also frequently displays areas of different weathering stages over different surfaces, such as the metacarpal illustrated in Figure 11.5, which ranges from WS 0 (unweathered) to WS 2. This bone was located, as is typical, with the unweathered surface in contact with the ground, and the WS 2 surface the uppermost and therefore the most exposed to environmental effects. Transitional areas of WS 1 bone are in between. Examples of WS 3 bone are depicted in Figure 11.2 (rib) and Figure 11.3 (vertebra), with rougher, fibrous patches of bone revealed under the spalling surface layers. More advanced weathering (WS 4) is depicted in Figures 11.6 through 11.8, in this example a juvenile cattle (*Bos taurus*) humerus whose main microscopic structure is plexiform bone. Deeper cracks have penetrated all the way to the marrow cavity, with areas of bone weathering carrying deeper into the cortex along these cracks. The surface is heavily spalled, with clear delamination following the underlying concentric osteonal bands (Figure 11.8). The majority of the cortex, however, still appears undamaged. The final stage of weathering (WS 5) is reached where

Figure 11.4 Sectioned metacarpal shaft of cattle (*Bos taurus*), showing intact inner cortex of plexiform bone, surface cracking, and a large patch of delamination (right side of photograph). Most of the visible exterior surface corresponds with WS 2. The scale is in cm.

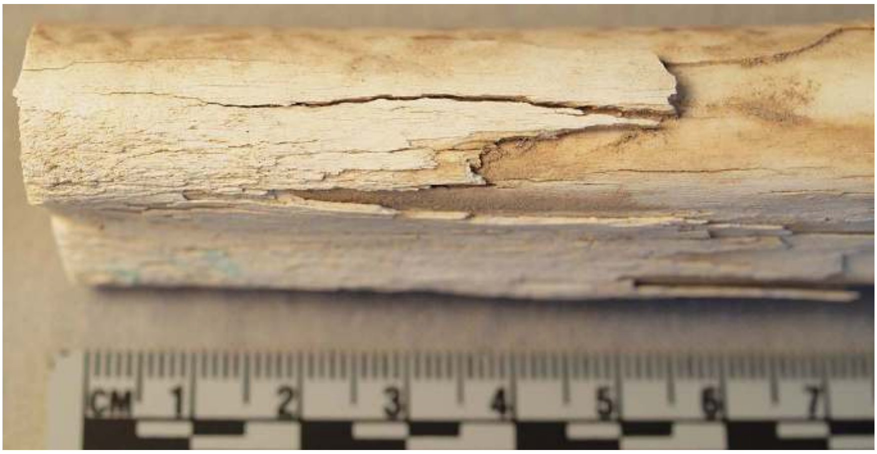

Figure 11.5 Sectioned metacarpal shaft (plexiform bone) of cattle (*Bos taurus*), showing the variability of weathering stages, ranging from unweathered (WS 0; top of photograph), to mildly weathered (WS 1; center of photograph), to weathered and delaminating (WS 2; bottom of photograph). Note also the unweathered bone exposed underneath the surface-delaminated area on the right.

Figure 11.6 Sectioned distal right humerus (plexiform bone) of cattle (*Bos taurus*), showing unweathered interior cortex structure underlying the highly weathered (WS 4) exterior.

the bone is falling apart into fragments (Figure 11.9), and most data about the element, size, type, development, species, and other taphonomic alterations are lost.

Effects of Solar Radiation on Bone Bleaching

Bleaching is one component of the overall suite of weathering changes and begins to show up early in the weathering process (see Chapter 12, this volume, for illustrations of sun bleaching and specific comparisons of this source of bone bleaching with other sources, including chemical). It is important to note that sun bleaching by itself frequently manifests on bones prior to them reaching WS 1 (see below), but this effect alone is insufficient to assign them to a stage higher than WS 0.

Beary (2005) examined the direct effects of solar (specifically, UV) radiation on the surface color of osseous remains under controlled experimental conditions. As he noted, the surface color of bone has gone largely unexplored in taphonomic research, with bone starting off its usual light beige color (i.e., "ivory" colored or similar descriptor) and becoming progressively bleached by solar radiation. Any quantification of this change was confined to comparison with *Munsell*® Soil Color Charts (Kollmorgen Instruments Corporation 1994). This procedure naturally includes all the variable effects of color determination, including differences in light source and interobserver and intraobserver

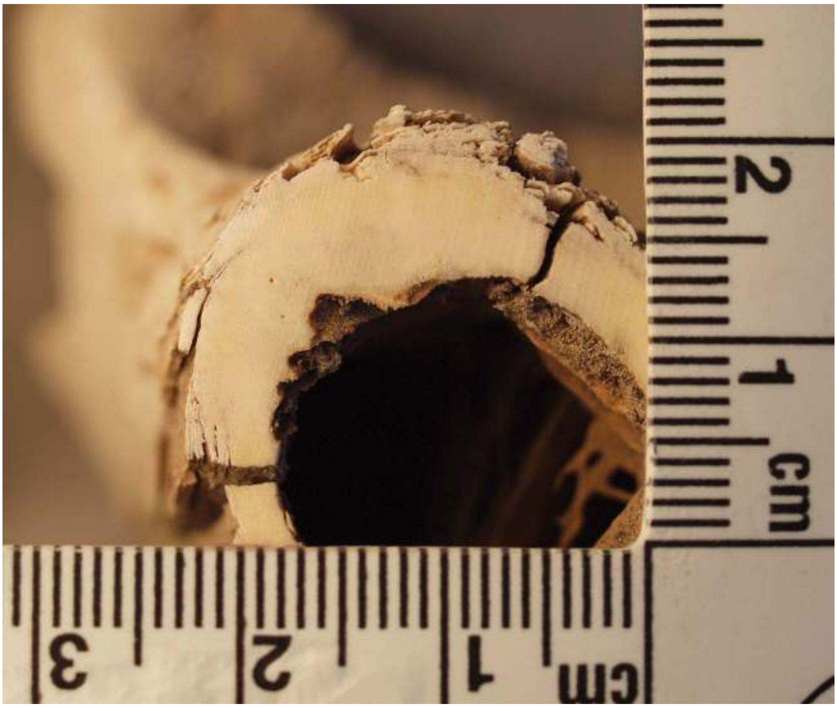

Figure 11.7 Sectioned distal right humerus of cattle (*Bos taurus*), showing unweathered interior cortex structure underlying the highly weathered (WS 4) exterior. Note the penetrating cracks reaching the marrow cavity and the delamination of the outer layers. The spalling of the osteonal layers of the plexiform bone is highly regular.

errors. In order to increase accuracy and replicability, Beary (2005) used a digital spectrophotometer to determine the degree of bleaching accrued on a sample of 60 white-tailed deer (*Odocoileus virginianus*) rib segments, half exposed to controlled dosages of generated UV light and half exposed to natural sunlight. Color changes were measured daily for over one month. He found highly significant relationships between the duration of UV insolation and the degree of color change (progressive bleaching). The results for the outdoor-exposed rib segments were more variable, as the effects of humidity also had a significant impact, including the degree to which wet bone reflects incident light to the spectrophotometer. The research indicated that bleaching begins immediately (even if it is not detectable by the human eye) upon exposure, although a terminal color was not reached in either portion of the study.

Pyle (2016) measured solar radiation exposure to sets of outdoor human remains (n = 19) at the Forensic Anthropology Center at Texas State University, San Marcos, TX. The control group (n = 10) was not exposed to solar radiation (wrapped in tarps), and the remainder (n = 9) were. Only the long bones, skull, scapulae, and innominates were utilized. These remains were observed weekly for signs of weathering after initial skeletonization. The median value for the appearance of sun bleaching was at 997 Accumulated Degree-Days (Megyesi et al. 2005) and at 47 calendar days. No significant differences were found in weathering rates between long bones and flat/irregular bones. In order to examine seasonal variation in sun bleaching, Stokes et al. (2020) exposed pig femora, scapulae, and ribs in open and shaded areas in Oxfordshire, UK, during summer and winter months.

Figure 11.8 Close up of sectioned distal right humerus (plexiform bone) of cattle (*Bos taurus*), showing unweathered interior cortex structure underlying the highly weathered (WS 4) exterior. Note the penetrating crack reaching the marrow cavity and the regular spalling of the outer layers, with intact osteonal layers (each around 200 μm thick) visible.

In summer, initial bleaching was visible at six weeks, and the bones obtained an off-white color by nine weeks. In winter, initial bleaching was visible at nine weeks, and the bones obtained an off-white color by 13 weeks. They also simulated "desert" sunlight conditions in a laboratory under artificial light; these samples showed sun bleaching as early as one week, but an off-white color was never reached even after eight weeks of exposure. The outdoor results of Stokes et al. (2020) are comparable to those of Junod (2013), who examined variable onset of weathering on defleshed white-tailed deer (*Odocoileus virginianus*) bones in a New England, USA environment. Some variation by microhabitat was detected: sun bleaching was first observed in forest and grassland sites three months after deposition but not observed in a (mostly open) wetland margin site until after four months. Schultz et al. (2018) found that sun bleaching could advance rapidly in the subtropical environment of Florida, USA. They examined select bones from four pig (*Sus scrofa*) carcasses exposed for nine months in shaded or open environments. Signs of sun bleaching occurred earlier at open sites, with a mean of around two months to reach their stage 1 (≤25% of surface

Figure 11.9 The final stage of weathering (WS 5): A bone disintegrating into fragments. The element can no longer be identified.

bleached) and three months for their stage 2 (26%–50% of surface bleached); these times averaged over three months and around five months, respectively, for shaded bones. More advanced bleaching encompassing more of the bones was obtained at longer exposure intervals.

Effects of Moisture and Wetting-Drying

The loss of moisture from a bone through surface exposure follows multiple pathways. These include the desiccation or decomposition of protective adhering soft tissue, the presence of which generally halts or greatly slows the weathering process. Continued exposure causes the bone to lose its internal water, although this can get replenished from precipitation cycles. More gradual is the decline in grease content as this decomposes, gets consumed, or slowly leaches to the surface and is lost to dissolution and consumption. Weathering in general appears to be slower where bones are kept moist and protected by vegetation and other forms of cover (Behrensmeyer 1978; Miller 2009), although moisture has long been recognized as an important factor in the breakdown of the organic component of bone (Hare 1974). Tappen (1994) and Pokines (2009) found weathering crack formation to be slower in a tropical rain forest environment than in open savannas and therefore likely partly related to moisture and/or drying cycles of the bones. These environments also presented much more uniform annual temperature with a complete lack of seasonal or daily freezing. Moisture in the bone, of course, is necessary for the damaging effects of freeze-thaw cycles to take effect (see “Effects of Freezing and Thawing” section, below). As bone is repeatedly wet and dried, crack formation may be enhanced by the shrinking and swelling of the material, although these effects have been little studied in the context of weathering. Waterlogged bone that dries rapidly may crack suddenly and extensively (Chapter 6).

Pokines et al. (2018) examined how wetting-drying cycles alone might contribute to subaerial weathering. They subjected a sample (n = 100) of dry ribs, first phalanges, vertebrae, and distal tibiae from white-tailed deer to 150 cycles of complete wetting-drying, using a daily cycle of soaking, then drying with a fan in a laboratory setting. Some slight previous cracking was already present and recorded photographically, so that any new cracking could be detected. Three bones reached WS 1 by 50 cycles, and five bones reached WS 1 by 75 cycles (Figure 11.10). Twenty bones reached at least WS 1 by 100 cycles, and three of these also displayed some minor surface delamination. After 125 cycles one bone (a distal tibia) had reached WS 2 (Figure 11.11), and 25 bones had reached WS 1 or WS 1 plus some minor delamination. After 150 cycles no additional bones reached WS 2, and 31 bones had reached WS 1 or WS 1 plus some minor delamination. Only 15 of 100 bones showed no cracking formation at all, down from a total of 79 at 0 cycles. Some differences also were noted by bone type, with the first phalanges exhibiting the least amount of change.

Repeated wetting-drying cycles clearly can play some role in subaerial weathering. Gifford (1984) noted, for example, that the bones in her sample on the shore of Lake Turkana, Kenya, that were subjected to repeated inundation by the lake had reached the most advanced stage (WS 3) after 30–34 months postmortem. For the wetting-drying

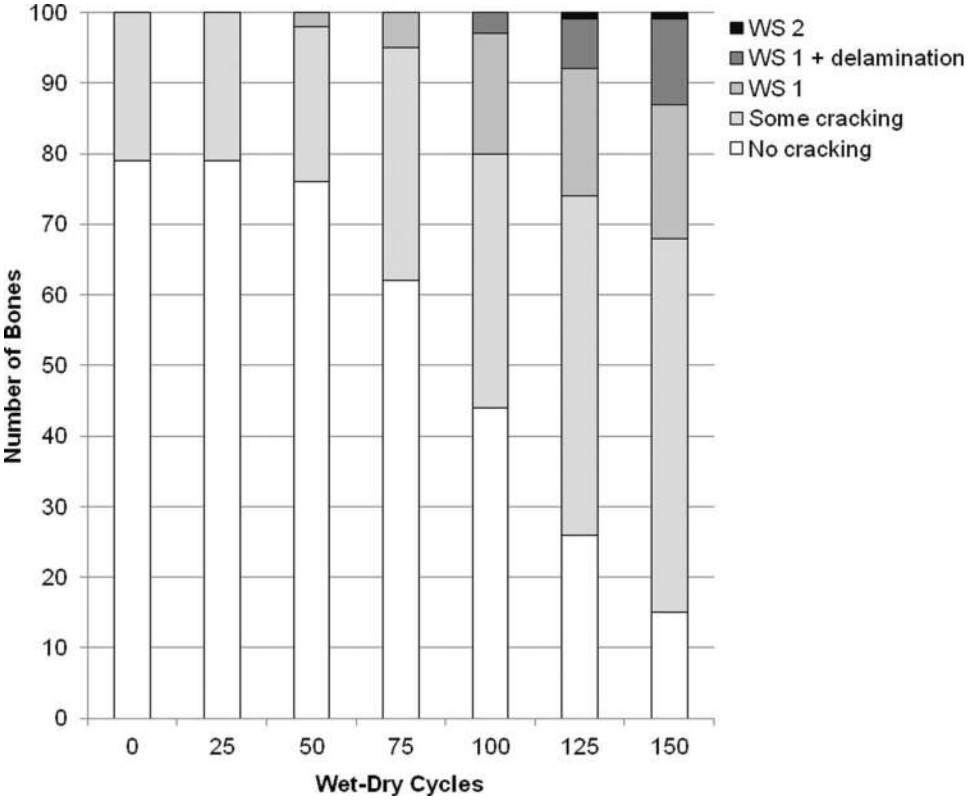

Figure 11.10 Progressive subaerial weathering characteristics of an experimental sample (n = 100) of dry white-tailed deer (*Odocoileus virginianus*) bones subjected to 150 repeated cycles of wetting-drying. (Adapted from Pokines et al. 2018:437)

Figure 11.11 Distal, previously butchered tibia of white-tailed deer (*Odocoileus virginianus*) after 150 cycles of experimental wetting-drying (Pokines et al. 2018), reaching WS 2 (surface delamination).

process to function, the bone must be at the intersection of the moisture source and the air so that the wet bone can dry out. Bone in natural settings likely does not go through such drastic cycles of wetting-drying (i.e., complete soaking followed by drying on a daily cycle). Daily dew formation during the warm season, however, may introduce enough moisture followed by drying out in the sun that some of these effects do accrue. More complete wetting would follow precipitation followed by drying, and long periods including freezing in the winter will not have any wetting-drying cycles at all. Bones deposited in damp areas also may stay continuously wet and not undergo as frequent wetting-drying cycles.

Effects of Heating and Cooling

Heating and cooling through the daily (or more rapid) cycles of direct sunlight upon a bone cause expansion and contraction. Pal and Saha (1989) found that in the range of −20°C to 20°C, the coefficient of thermal expansion in a human tibia ranges from 23 to 32×10^{-6}/°C (i.e., the bone will undergo a linear fractional change in size in the range of 0.000023–0.000032/°C within this range). From 30°C to 60°C (i.e., the interval one would expect bones and other objects lying in direct sunlight in warm environments to attain), they found that the linear fractional change was larger: 37.1×10^{-6}/°C. The normal in vivo temperature of human bone is 37°C. Depending on the depositional environment, temperature swings of tens of °C per day would be expected for bone lying on the surface between when direct sunlight strikes during day and night or other exclusion of sunlight.

The role that thermal expansion and contraction play in the weathering of bedrock has been examined (Hall 1999). As the cycles of thermal expansion and contraction accrue, material fatigue accumulates, which may cause microfracturing (thermal stress fatigue) or sudden failure (thermal shock) (Hall 1999:48). This model applies to bone, where expansion/contraction damage may accrue slowly over many diurnal cycles and sudden changes in temperature may induce localized failure of the bone structure (Conard et al. 2008), especially in parallel to the heterogeneous structures of osteons including cement lines, resorption spaces, and central canals (Skedros et al. 2005). Bone, however, is more homogenous in composition overall than many types of rock, since the latter may have a highly heterogeneous crystalline structure (such as granite), be composed of heterogeneous sedimentary materials, have metamorphic recrystallization, or have veins of different minerals interrupting the main structure. Differing rates of thermal expansion/contraction in these adjacent mineral crystals in rocks therefore may cause fracturing along their boundaries. Expansion and contraction may explain, however, why the much more highly mineralized (and therefore more brittle) teeth (Currey 2002) with their different structural organization (Weiner and Wagner 1998) often have fractured to a higher degree than their associated cranium or mandible. This different cracking and fragmentation pattern is one reason why teeth are normally excluded from designations of weathering stage for a set of remains.

Effects of Freezing and Thawing

Freezing can cause microscopic cracking of bone (Tersigni 2007; Turpin 2017). Beyond the linear expansion and contraction of bone with changes in temperature, freezing of water within the cracks already formed within a bone or in other internal spaces has a high potentially destructive force (Guadelli 2008, 2015; Matsuoka 1996). Around 12% of fresh cortical bone volume consists of pore spaces (Nielsen-Marsh et al. 2000), so even the denser portions of a bone can absorb water. Water reaches its maximum density at 4°C, and it undergoes ~9% volume expansion dropping from 4°C to 0°C as it freezes and the H_2O molecules form a hexagonal crystal structure—hence, the property of ice floating. Since water exerts up to 30,000 lb-force/in^2 (207 MPa) as it expands while freezing (Matsuoka and Merton 2008), this force has the greatest potential in the natural environment to spread existing cracks in bone wider and deeper and propagate them longitudinally. The maximum tensile strength of rock (and bone) is far exceeded by this force, especially force directed transversely to bone (Pietruszczak et al. 2007; Turner et al. 2001; Weiner and Wagner 1998). Subsequent thawing then allows the water to penetrate more deeply into these newly expanded cracks before refreezing perhaps during the same diurnal cycle (Matsuoka and Merton 2008). Multiple trips through this cycle may be the dominant destructive force in temperate zone physical weathering of bone, although this process needs further controlled experimentation. These processes are well understood in the geological sciences regarding the mechanical breakdown of rocks (Hall and Thorn 2011, 2014; Matsuoka and Merton 2008; Yavuz 2011). The rapidity of this cycling and its occurrence multiple times per day in spring and fall in the temperate zone (Matsuoka 1996) may work to destroy bone faster than during summer and winter, with their fewer changes in temperature moving above or below the freezing point. Snow cover, partial burial, or ambient temperatures remaining below freezing for long periods would act to inhibit the rate of weathering (Bertran et al. 2015; Miller 2009; Texier et al. 1998). Habitats that cycle through freezing/thawing most frequently (i.e., the temperate zone) may weather bone more rapidly than habitats with more constant temperature above (subtropical and tropical) or below (boreal forest and tundra) this middle range. Locations along bodies of water, with their greater humidity, are also likely to increase the incidence and severity of frost damage (Matsuoka and Merton 2008).

Pokines et al. (2016a) examined the effects of repeated freeze-thaw cycles upon a sample (n = 93) of already dry, fused/unfused metapodials of white-tailed deer. These were subjected to up to 75 freeze-thaw cycles in a laboratory setting, with samples withdrawn every 25 cycles for histological examination of cracking. Macroscopic changes included

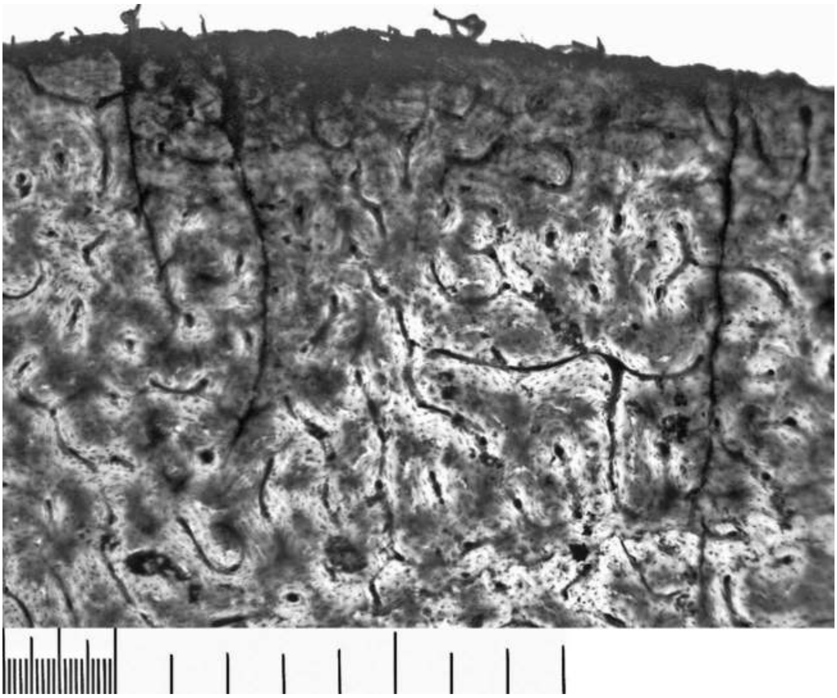

Figure 11.12 Section of metapodial of white-tailed deer (*Odocoileus virginianus*) after being subjected to 75 experimental cycles (Pokines et al. 2016a) of freezing/thawing, (4x magnification). Note the dark crack formation through the plexiform bone structure, with the bone surface visible at the top. The scale is in 0.1 mm increments.

progressive surface cracking similar in appearance to naturally weathered bone, but no bone clearly reached WS 1 over this interval. Histologically, fine cracks were noted to develop, penetrating through the plexiform bone structure (Figure 11.12). From these results it is likely that additional cycles would eventually bring about advancement in weathering stage.

Other experimental research into freeze-thaw cycles also has produced progressive cracking development. Guadelli (2008, 2015) and Guadelli and Ozouf (1994) reported on a sample of different bone types (fresh bone [n = 5], fresh antler [n = 2], fossil bone [n = 4], and fossil teeth [n = 2]) run through 3149 daily freeze-thaw cycles. The effects upon the fresh bone subsample were variable: some had visible effects as early as 63 cycles, but none were fragmented apart by the end of the experiment. Most cracking was longitudinal and on the surface, but some of the fresh bone developed delamination, with the cortex splitting apart in thin layers (Guadelli 2015). The fresh antler subsample developed even less cracking than the fresh bones subsample, possibly due to its lower degree of mineralization and less-organized structure compared to fresh bone. The fossil subsamples cracked and fragmented relatively early and showed high degrees of fragmentation by the end of the experiment. Reduced organic content therefore may affect how osseous materials can respond to this type of taphonomic process, given that the organic content is responsible for a bone's elasticity and acts as a barrier to further crack propagation. This aspect of subaerial weathering research requires additional experimentation (Bertran et al. 2015).

Theoretically, any taphonomic process increasing the amount of cracking or pore space in bone would increase its susceptibility to freezing/thawing damage. These processes might include focal destruction by invading fungi (Chapter 2) or plant rootlets (Chapter 5), indicating that habitats with high amounts of biological activity may predispose bone to a greater degree of this potential source of weathering damage, provided that they also have seasonal cold phases (including temperate environments).

Effects of Mineral Crystallization

The formation of crystals within bone also can cause cracking, as these minerals expand and force apart the existing bone structure, much as freezing water forms expanding crystals (Trueman et al. 2004). Other effects of mineral crystallization may cause expansion, including differential thermal expansion of the porous substance versus the impregnating minerals, osmotic swelling of clays, hydration pressure, and enhanced wet/dry cycling (Doehne 2002; Prassack 2011). Minerals that commonly crystallize near the surface of bedrock include halite (NaCl), nitratite ($NaNO_3$), gypsum ($CaSO_4 \cdot \bullet 2H_2O$), calcite ($CaCO_3$), and dolomite ($CaMg(CO_3)_2$), depending upon the local groundwater solution and other factors (Matsuoka 1995).

This phenomenon has been noted directly affecting bone. Behrensmeyer (1978), Cutler et al. (1999), and Trueman et al. (2004) noted the frequent presence of alkaline soils in Amboseli Park, Kenya, where they observed long-term large mammal bone weathering. In some cases, weathering was more advanced on the bone surfaces in contact with the ground than on the opposite surface exposed to more direct solar radiation. They attribute this reverse pattern to the formation of crystals on the undersides of bone that forced apart cracks and increased the overall degree of fragmentation. This phenomenon is known to damage archaeological monuments and artifacts and is indeed one of the primary forces acting against their long-term preservation (Doehne 2002; Johnson 1998; Rodriguez-Navarro and Doehne 1999). Matsuoka (1995) described how salt crystal formation can fracture bedrock in a similar manner, even in cold Antarctic desert conditions. Crystallization therefore may affect bone weathering in environments where other sources of weathering damage are less prevalent.

Key to this taphonomic (diagenetic) process is the infiltration of groundwater with soluble/exchangeable minerals from the soil (Pate et al. 1989; Pate and Hutton 1988; Sillen 1989). As this solution reaches the surface of bone and other porous materials, the water evaporates, leaving behind the minerals to crystallize (Rodriguez-Navarro and Doehne 1999). This process affects archaeological monuments even in arid environments, such as the well-known tombs carved directly into sandstone at Petra, Jordan, by the Nabataean culture and dating back to the sixth century BC. The effect is concentrated at the surface layers where the minerals crystallize, with flaking exposing deeper portions of the rock that then become the new surface layer and are exposed to attack. This repeated spalling of the surface layer gradually erodes away the structure of the stone building or monument and is the focus of much conservation effort. Other factors in their weathering include the dissolution of more-soluble minerals, weakening the overall structure (Walderhaug 1998), similar to the breakdown of the organic component through digestion by microbes and chemical breakdown (Nielsen-Marsh et al. 2000; Smith et al. 2005; Turner-Walker 2008), weakening its overall resistance to weathering. The type of rock also plays a role, as limestones may be more susceptible (Ouacha et al. 2013).

In a study of bones from the Amboseli Basin, Kenya, Trueman et al. (2004) thin-sectioned multiple weathered bones from known large mammal species to detect the microscopic effects of weathering. They found within pore spaces formed by natural bone structures or from postmortem alteration that several mineral types had recrystallized from uptake from the groundwater, including calcite, barite, dahlite, crandallite, trona, and possibly sepiolite, with calcite the most common. The formation of these crystals alters the physical structure of the bones, making their composition less homogenous and more prone to thermal stress, as discussed earlier. The diagenetic effect of recrystallization of bone minerals themselves also may contribute to this cause of weathering. Dissolved bone minerals in the soil water solution can recrystallize the intact hydroxyapatite, also altering the microscopic structure of the bone (Hedges et al. 1995; Nielsen-Marsh et al. 2000; Trueman et al. 2004). The differential thermal expansion and contraction of both types of crystals could aid in the formation of microcracks within the bone, speeding the rate of weathering in locations with a high surface evaporation rate. The recrystallization of the hydroxyapatite also weakens the bone and makes it more susceptible to breakage from mechanical forces, and this effect is similar to that caused by recrystallization due to calcination of burned bone (Stiner et al. 1995).

Effects from Previous Coffin Burial

Human remains from coffin burials are sometimes churned to the surface through subsequent excavation or erosion (Chapter 5). Being found in or adjacent to cemeteries in urban and suburban areas, it is expected that these remains have not been on the surface for multiple years in most cases prior to their discovery and reporting to law enforcement. These bones, however, can show significant weathering (Figures 11.13 and 11.14),

Figure 11.13 Former cemetery remains, human innominate that was later exposed on the surface and developed advanced subaerial weathering (WS 3); Massachusetts, USA. The scale is in cm.

Figure 11.14 Former cemetery remains, human mandible. The left ramus portion was later exposed on the surface and developed subaerial weathering; Massachusetts, USA.

reaching WS 3 in some cases (Pokines et al. 2016b). While some of this weathering is explicable by delayed discovery intervals, some cemetery bones appear to be weathering rapidly. Subaerial weathering in these cases may be given a large head start by the decades that the organic component of the bones had to break down prior to their surface exposure. With reduced collagen structure to help the bones resist crack formation, weathering stage advancement may proceed more rapidly. Sun bleaching also may be more rapid due to the reduced organic content, as a greater proportion of the bones' content is made up of the (white) hydroxyapatite mineral component. In some cases, areas of bone can become highly sun-bleached without the usual amount of accompanying cracking (Figure 11.15).

Other Effects from Terrestrial Surface Exposure

General Changes

Other taphonomic changes often accompany weathering in surface environments. Bones exposed on terrestrial surfaces often display some taphonomic effects in common with buried remains (Chapter 5) for roughly one half of their surfaces in contact with the topsoil. Two separate hemispheres differing in many of their taphonomic effects therefore often characterize these remains. Most common among these on the exposed portions of bones is algae growth on surfaces, which commonly is found on lightly weathered bones (Figure 12.13, Chapter 12, this volume). The environmental conditions needed for the algae to grow (nutrients, moisture, and sunlight) also favor bone weathering. Algae, of course, can develop on submerged bone in shallow (fresh or salt) water (Haefner et al. 2004), so

Figure 11.15 Former cemetery remains, human frontal that was later exposed on the surface and developed subaerial weathering, with some brightly sun-bleached areas that displayed no surface cracking; Massachusetts, USA. The scale is in cm.

its presence is only an indicator of sunlight and wet conditions to some degree and not uniquely surface deposition. In general, algae forms on the more exposed portion of the bone, just as these portions also tend to have the most advanced weathering. Very dry conditions, however, can lead to the death of the algae, especially on these more exposed (and more likely to desiccate) bone portions. Skeletal elements within the same surface scatter often have differing degrees of algal growth, from none visible to extensive, based upon minor differences in microhabitat (amounts of sunlight, moisture, etc.), in the same way that these elements display different degrees of weathering, inter- and intra-element.

Lichens and moss are also common growths on bone and other solid objects lying exposed on the ground surface. Mosses (Division Bryophyta) are simple plants that are limited in size due to their lack of a vascular system and derive energy through photosynthesis. They also therefore must have a moist (mesic) environment to survive. Their growth on bone can leave behind surface staining (Chapter 12). Lichens (Figure 11.16) are symbiotic life forms consisting of a fungus (most commonly within Division Ascomycota) and photosynthetic algae or cyanobacteria. They can grow on a wide variety of substrates (living and nonliving) and in a range of environments, including dry (xeric) conditions. Their derivation of energy through photosynthesis also means that their presence is indicative of sunlit terrestrial environments. Lichens growth rates have even been applied as a type of dating on archaeological sites, although these are normally confined to dating rock structures or geological formations (Benedict 2009). The generally slow growth rates of lichens mean that they are unlikely to cover extensive portions of a bone, since the bone will be

Figure 11.16 Example of lichens growth on bone exposed for over 40 years in Idaho, USA. The scale is in cm. (Image courtesy of Adeline Lustig.)

exposed on the surface and subject to other destructive forces throughout that interval. The degree to which lichens might erode bone surfaces is little known, although they do contribute to the surface weathering of rocks (Banfield et al. 1999). Fungi are known to cause microscopic focal destruction of bone (Chapter 2).

Massachusetts, USA Forensic Sample

In order to determine the common taphonomic effects incurred during terrestrial surface exposure to human remains in the New England region, Pokines (2016) examined a sample of cases (n = 22) at the Office of the Chief Medical Examiner, Boston, Massachusetts, USA. These cases were supplemented with new data from the same environment (total n = 42). These data were compared to a sample (n = 26) of white-tailed deer (*Odocoileus virginianus*) remains from the same environment. This species is comparable in body mass to human, is common throughout the state, and is frequently reported to law enforcement as being possibly human in origin (Pokines 2015). The majority of cases came from forested environments, and all human cases except one were adult or consistent with adult. All cases were composed of skeletonized or mostly skeletonized remains, and

Table 11.2 **Skeletal Representation for Human (n = 42) and *Odocoileus virginianus* (n = 26) Skeletonized Cases Recovered from Terrestrial Environments in Massachusetts, USA**

Skeletal Portions	Human (n = 42)		*Odocoileus virginianus* (n = 26)	
Recovered	n =	%	n =	%
Isolated skull or cranium	6	14.3	0	0.0
Isolated mandible	2	4.8	0	0.0
~Complete skeleton	13	31.0	0	0.0
Partial cranial + postcranial skeleton	15	35.7	0	0.0
Partial postcranial skeleton only	5	11.9	13	50.0
Two postcranial elements only	1	2.4	1	3.8
Isolated postcranial element	0	0.0	12	46.2

Source: Pokines, J. T. (2016) and new data; used with permission, *Journal of Forensic Identification.*

cases with substantial soft tissue were excluded so that the effects accrued by exposed bones could be examined. Three (7.1%) of the human cases were from individuals found hanging, but at least some of the bones had become disarticulated and were in contact with the ground surface.

Skeletal representation is compared in Table 11.2. The human cases tended to be much more complete. White-tailed deer cases consisted only of isolated remains (46.2%), two postcranial bones (3.8%), or a partial postcranial skeleton (50.0%), likely reflecting some kind of filtering process where deer cranial remains are recognized as nonhuman and not reported to law enforcement (Pokines et al. 2017). The human sample included no isolated postcranial elements cases but did include isolated skulls/crania (14.3%), mandibles (4.8%), or two postcranial elements together (2.4%). Approximately complete (31.0%), partial cranial and postcranial (35.7%), and partial postcranial (11.9%) skeletons made up the bulk of the sample. The human cases therefore averaged a much higher amount of bone and had more chances to manifest any particular taphonomic effect, which likely affected the overall representation.

Thirty-two (76.2%) of the human cases had sediments and/or humus adhering, and 36 (85.7%) had variable patches of surface staining; six deer (23.1%) had sediments and/or humus adhering, and 16 (61.5%) had patches of surface staining (Table 11.3). This staining was typically medium brown and found in association with or at least on the same side of the bone as the adhering sediments/humus, while the rest of the bone often retained its natural color (Chapter 12). Some patches of staining displayed more variable colors, ranging from reddish to brown or even darker and were associated with decomposition of soft tissues. These deep, darker, and variable staining patterns differ with bones from other contexts, such as those from coffin burials (Chapter 5), which tend to be much more uniform in color. Thirteen human cases (31.0%) and one deer case (3.8%) had plant roots adhering/infiltrating, which is a taphonomic effect often associated with buried/cemetery bones. Similarly, six human cases (14.3%) had acidic soil corrosion among their soil-stained areas, but this was more localized than typically found on buried bones.

All bones in 35 (83.3%) of the human cases were in WS 0 (unweathered), with 16 (38.1%) of these cases showing some sun bleaching but no fine surface cracking characteristic of

Table 11.3 **Taphonomic Effects on Human (n = 42) and *Odocoileus virginianus* (n = 26) Skeletonized Cases recovered from Terrestrial Environments in Massachusetts, USA**

Taphonomic	Human (n = 42)		*Odocoileus virginianus* (n = 26)	
Effect	n =	%	n =	%
Sediments/humus adhering	32	76.2	6	23.1
Localized soil staining	36	85.7	16	61.5
Adhering plant material	16	38.1	0	0.0
Plant roots/etching	13	31.0	1	3.8
Acidic soil corrosion	6	14.3	0	0.0
Weathering stage:				
0; Not sun-bleached	19	45.2	7	26.9
0; Sun-bleached	16	38.1	10	38.5
1	6	14.3	9	34.6
2	1	2.4	0	0.0
Algae	18	42.9	5	19.2
Moss	1	2.4	0	0.0
Desiccated soft tissue	27	64.3	12	46.2
Adipocere	16	38.1	1	3.8
Bone preservation:				
Greasy	18	42.9	10	38.5
Organic sheen	24	57.1	15	57.7
Chalky	0	0.0	1	3.8
Carnivore gnawing	26	61.9	10	38.5
Rodent wet-bone gnawing	2	4.8	0	0.0
Rodent dry-bone gnawing	15	35.7	9	34.6
Mold	3	7.1	0	0.0
Live maggot activity	2	4.8	0	0.0
Dry maggot casings only	16	38.1	0	0.0
Other live arthropods	9	21.4	0	0.0
Associated with clothing	19	45.2	N/A	N/A
Thermal	1	2.4	0	0.0
(Hanging)	3	7.1	N/A	N/A

Source: Pokines, J. T. (2016) and new data; used with permission, *Journal of Forensic Identification.*

WS 1. Six (14.3%) of the human cases had at least one bone reach WS 1. One human case had reached WS 2 (2.4%). All bones in 17 (65.4%) of the deer cases were in WS 0, and 10 (38.5%) of these cases showed sun bleaching; nine (34.6%) deer cases had at least one bone reach WS 1. Diffuse, green algae staining was present on some bone in 18 (42.9%) human cases and five (19.2%) deer cases, and one human case (2.4%) had moss growth.

Twenty-seven human (64.3%) and 12 deer (46.2%) cases had some desiccated soft tissue still adhering, which was in part by sample design and the exclusion of actively decomposing human cases. Adipocere was present in 16 (38.1%) human cases and one (3.8%) deer case. Bone condition was scored as greasy, not greasy but retaining an organic sheen, or chalky/

dull. Eighteen (42.9%) of the human cases and 10 (38.5%) of the deer cases were greasy, 24 (57.1%) of the human cases and 15 (57.7%) of the deer cases had organic sheen, and no human case and one (3.8%) white-tailed deer case were scored as chalky; these proportions differ greatly from buried remains, where greasiness is rare and chalkiness is common (Chapter 5).

Some manifestation of carnivore gnawing (Chapter 9) was noted in 26 (61.9%) human cases and 10 (38.5%) deer cases, likely from canids or smaller carnivores. Two human cases (4.8%) and none of the deer cases had rodent wet-bone gnawing (Chapter 9); rodent dry-bone gnawing was noted in 15 (35.7%) human cases and nine (34.6%) deer cases. In addition, three human cases (7.1%) and none of the white-tailed deer cases had mold growth (associated with soft tissue or exuding grease). Insect casings consistent with blow flies (Calliphoridae) were present in 16 human cases (38.1%) and zero deer cases, and some residual live maggot activity despite the sampling design was present in two (4.8%) human cases. Other live arthropods, including spiders (Araneae) were present in nine (21.4%) human cases. Maggot casings were often found in protected locations, such as inside clothing, which was present in 19 (45.2%) of the human cases. One human case (2.4%) had a bone with a small area of carbonization (Chapter 14). This thermal alteration was unrelated to the death event and occurred after decomposition and dispersal to a location near an unrelated outdoor fire pit.

Direct Effects of Precipitation

Some cases have been recorded of more direct impacts of precipitation upon bones, in the case of hailstones striking exposed remains. Maijanen et al. (2016) noted an episode of extreme storm damage that occurred to exposed skeletons at the outdoor Anthropology Research Facility in Knoxville, Tennessee, USA. Thirty of the approximately 125 skeletons exposed to this extreme weather event had taphonomic effects attributable to hailstones or fallen branches/other objects, but most of the damage was assessed to be from hailstone impacts in the golf ball to baseball size range. Most damage was to the flat bones (scapulae, ribs, and innominates), and the skull, long bones of the legs, ribs, and vertebrae also were affected. Maijanen et al. (2016) characterized hailstone damage as oval/circular depression fractures, and irregular damage that was larger on average was either hailstone damage or the result of other heavy falling objects. They did note that multiple individuals in their sample (11 of 30) had died of cancer, which could have led to reduced mineralization of their bones. The hailstones recorded in this case were particularly large, so it is possible that lesser storms could produce more subtle damage or none at all.

Weathering and the Postmortem Interval

Applications to Forensic Anthropology

The use of subaerial weathering data in forensic anthropology, apart from contextual information, is primarily to estimate the PMI of a skeletal assemblage in situations where other types of data no longer apply. These include decomposition stage (Chapter 3), the timing of which in a known temperature environment may allow estimation of the PMI (Megyesi et al. 2005), arthropod succession, or other more immediate changes in a recently deceased individual such as cooling or degree of rigor mortis (Geberth 2006). Past the skeletonization stage, further breakdown of the skeleton itself often is the only available method of PMI estimation derived from the remains themselves, as opposed to using artifactual evidence found with the remains. Bone weathering therefore fills the gap between early (largely soft tissue) methods and ^{14}C determinations of bone age (Chapter 1).

Weathering data also may give, along with soil staining, algae growth, and water ring formation, a clear indication that a bone from a surface assemblage has been moved recently if the most bleached, weathered surface (in most temperate settings) is no longer the most exposed surface of the bone. This information may be relevant in the documentation of recent site disturbance, including the corroboration of witness testimony regarding their discovery of a surface skeletal deposit. Weathering alterations also must be distinguished from other forms of taphonomic alteration (see "Confusion with Other Taphonomic Effects" section, below).

Effects of Macroenvironment

The rate of weathering (Table 11.4) varies across regions, based on broad differences in temperature regimes, precipitation, and vegetation, and these parameters are major factors when estimating PMI from weathering stage (Ubelaker 1997). Previous research has demonstrated that skeletal remains deposited in cooler, temperate climate areas can experience a longer duration of survival (Andrews and Armour-Chelu 1998; Andrews and Cook 1985; Fiorillo 1995; Miller 2009) than skeletal remains deposited in a semiarid savanna climate (Behrensmeyer 1978; Coe 1978; Isaac 1967; Tappen 1992, 1994; Western and Behrensmeyer 2009). Furthermore, rainforest environments are known to slow the rate of weathering and extend the period of bone survival due to constant moisture, lack of freeze/thaw cycles, and dense protective vegetation (Kerbis Peterhans et al. 1993; Pokines 2009; Tappen 1994, 1995). These patterns generally indicate that the rate of weathering is slower in colder environments and locations where bones are protected from direct sunlight and that warmer climates with a high UV index and/or high daily fluctuating temperatures tend to accelerate the rate of weathering. This process remains variable, as other previous research has indicated contradictory results (Andrews and Whybrow 2005).

Miller (2009), in a large landscape study of natural osseous deposition in Yellowstone National Park (USA), noted that individual surface-exposed elements could survive to a recognizable state (WS 4) for over 200 years as determined by ^{14}C dating. Snow covering the bones for at least half of each year likely is a dominant factor in their long-term preservation. Andrews and Cook (1985) studied bone modifications of a single cattle carcass in a temperate environment in the UK and determined that the skeletal elements did not portray any signs of weathering (WS 0) after an eight year period. These elements were largely protected by the local vegetation and terrain. Similarly, in central Wales, Andrews and Armour-Chelu (1998) studied a surface assemblage from natural deaths of sheep and found that the majority of skeletal elements showed no signs of weathering, and none of the bones had reached the most advanced stage of weathering (WS 5). The time of exposure was unknown, but continuous observations indicated that weathering rates tend to be much slower when compared to equatorial Africa (Behrensmeyer 1978). Fiorillo (1995) also noted a prolonged survival rate of ungulate remains studied in a sub-alpine, open grassland climate of southwest Colorado, USA. Colder temperatures led to depressed microbial

Table 11.4 Rates of Osseous Subaerial Weathering in Different Environments

Location/Environment and Sample	Weathering Rate Observations	Source(s)
	Savanna	
Amboseli Park, Kenya Semi-arid savanna with a mean annual temperature of 26°–34°C and a mean annual rainfall of 350 mm. The area is a flat-lying basin with minimal vegetation coverage, and soils tend to be alkaline. The remains are of multiple large species.	WS 0: 0–1 years WS 1: 0–3 years WS 2: 2–6 years WS 3: 4–15+ years WS 4: 6–15+ years WS 5: 6–15+ years	Behrensmeyer (1978)
Tsavo (East) National Park, Kenya Semi-arid grassland with a mean annual temperature of 28°C. Mean annual rainfall is 538 mm but is highly variable. Remains were of two subadult and one adult African elephant (*Loxodonta africana*) carcasses that died at known times.	Cortical flaking occurred within 4 years of exposure, with an estimated bone survival interval of at least 20 years.	Coe (1978)
Parc National des Virunga, Zaire Medium and tall grass savannah with a mean annual rainfall of 900 mm. Dry seasons are shorter and less severe than other East African savannas. Soils generally have a neutral pH. Remains were from a single cape buffalo (*Syncerus caffer*) skeleton found recently dead, still greasy, with some connective tissue, and without previous cracks.	WS 1 was reached two years after death, and WS 2 was reached four years after death. The weathering rate is comparable to Amboseli Park, Kenya (Behrensmeyer 1978), but the duration of the study is not sufficient for the later stages.	Tappen (1992, 1994, 1995)
Olorgesailie, Kenya Mixed acacia brushland within a savanna environment. The bones of subadult *Capra hircus* and some *Bos taurus* were protected under wire mesh and wood frame.	Some elements reached approximately WS 4 within seven years (based upon descriptions).	Isaac (1967)
Lake Turkana, Kenya The remains of wild ungulates that died in a strip of grassy flats near the shore were assessed at 6–10 months and 30–34 months after death. Some inundation from the lake occurs.	6–10 months: no bones above WS 1, some still at WS 0. 30–34 months: no bones above WS 3, most at WS 2 or WS 1, none at WS 0.	Gifford (1984)
	Tropical Rain Forest	
Ituri Rain Forest, Zaire Tropical rain forest with dense vegetation and an annual rainfall average of 1900 mm and notable wet and dry seasons. Mean annual temperature is 31°C, and soils are generally acidic, with a pH of 4.0–4.25. Remains were of eight *Loxodonta africana* skeletons that were killed and eaten by inhabitants of the Ituri.	Bone weathering is significantly delayed and sometimes absent due to dense vegetation and the wet environment. PMI is known for only some of the bones. WS 0 was seen up to 16 years after death at one site, and the most advanced weathering stage observed (WS 3) was noted after 15+ years at another site.	Tappen (1994)

(Continued)

Table 11.4 ***(Continued)*** **Rates of Osseous Subaerial Weathering in Different Environments**

Location/Environment and Sample	Weathering Rate Observations	Source(s)
Papua New Guinea Tropical rain forest with generally acidic topsoil and less acidic subsoil. Dense forest canopy and/or aircraft wreckage provided partial protection. Remains were from an aircrew of ten individuals from a WWII airplane crash, the remains of which were largely at the surface or thinly buried over that interval by accumulating decaying leaf litter.	No weathering (WS 0) occurred after 58 years, although not all remains were exposed for this full time.	Pokines (2009)
Temperate Grassland		
UK Pasture with surrounding woodlands. Remains were of a single *Bos taurus* carcass deposited at the base of a slope and sheltered by vegetation and topography.	No weathering (WS 0) occurred after eight years, with some natural scree slope burial of elements.	Andrews and Cook (1985)
Nebraska, USA Grassland with a mean annual temperature of 9°C and mean annual precipitation of 403 mm. Remains were of one subadult and two adult *Bos taurus* carcasses that had died at known times.	WS 1 was reached by three years, WS 2 was reached by five years, and WS 4 was reached by 13 years.	Potmesil (2005)
Nebraska, USA Grassland/prairie, open and unshaded. Bones were of adult *Bos taurus* and juvenile *Sus scrofa* selected from domestic carcasses that had died of natural causes at known times.	WS 0: 0.2 years WS 1: 1–3 years WS 2: 3–5 years WS 3: 5–8 years WS 4: 7–8 years WS 5: 7–8 years	Fiorillo (1989)
Boreal/Mixed Forest		
Yellowstone National Park, USA Primarily boreal forest with a mean annual temperature of 4.6°C and mean annual precipitation of 387 mm. Snow pack is deeper than one foot for at least half the year, and vegetation densities are higher compared to Amboseli Park, Kenya. Annual freeze-thaw cycles total >50. Remains were of local large fauna.	WS 0: 0–1 years WS 1: 0.3–6.5 years WS 2: 2–10 years WS 3: 3–20+ years WS 4: 6.5–200+ years WS 5: 35–200+ years	Miller (2009, 2011, 2012)
Southern Ontario, Canada Mixed deciduous and coniferous forest with average monthly temperatures ranging from 6° to 23°C and total monthly precipitation ranging between 20 to 120 mm. Soil pH is neutral. Defleshed *Sus scrofa* femora and metatarsals were set in wooden-framed wire cages which did not have a floor.	Longitudinal cracking (WS 1) first appeared after six months. No cortical bone flaking (WS 2) was observed after 9.5 months.	Janjua and Rogers (2008)

(Continued)

Table 11.4 ***(Continued)*** **Rates of Osseous Subaerial Weathering in Different Environments**

Location/Environment and Sample	Weathering Rate Observations	Source(s)
Alpine/Tundra		
Colorado, USA Sub-alpine, open grassland with annual temperatures that range from -40° to 32°C and mean annual precipitation of 325 mm. The remains consisted primarily of medium to large ungulates, rodents, and lagomorphs, as well as some bird and fish specimens.	PMI is unknown. The majority of bones were recorded as WS 0, possibly a result of the predominantly low temperatures.	Fiorillo (1995)
Qikirtaq Island, Canada Semi-arid arctic herbaceous tundra with a mean annual temperature of -7°C and a mean annual precipitation of 310 mm, with 53% falling as snow. Surrounding soils are generally acidic. Remains were of local, medium to large marine and terrestrial fauna.	AMS ^{14}C dating indicated an age range of 1,900–2,500 years BP. Bones were excavated from three main archaeological levels, and bone preservation was excellent, with the majority of bones recorded as WS 1 and WS 2.	Todisco and Monchot (2008)
Gavarnie, Central Pyrenees, France The Taillon site was located at 2,674 m and has a mean annual air temperature of 0°C and a mean annual precipitation of 1,500-1,800 mm/year. Burned, fresh, fossil, and already dry bones were deposited inside and outside of a small cave.	All fresh bones stayed at WS 0 after four years of exposure. Burned, fossil, and already dry bones developed or increased surface cracking and underwent some fragmentation.	Bertran et al. (2015); Mallye et al. (2009)
Mediterranean		
California, USA Mediterranean environment, with experiment using *Sus scrofa* ribs, femora, and vertebrae exposed to sun or shade microenvironments.	No bone had advanced past WS 0 after 133 days. Some sun bleaching of the bones in the sun, no bleaching for those in shade.	Morris (2013)
Desert		
Abu Dhabi, United Arab Emirates Wadi bed in a desert environment that lacks vegetation and experiences large daily temperature fluctuations and high solar radiation. Remains were from a single *Camelus dromedarius*.	Weathering rates appeared to be slower, with WS 1 reached only by a few elements after two years (initial contact point). After eight years, no elements had reached WS 2; WS 2 was reached on some elements by 10 years, and WS 3 was reached on some elements by 15 years. Bones that had become buried showed little or no weathering after 15 years.	Andrews and Whybrow (2005)

(Continued)

Table 11.4 ***(Continued)*** **Rates of Osseous Subaerial Weathering in Different Environments**

Location/Environment and Sample	Weathering Rate Observations	Source(s)
Wadi Enoqiyya, Azraq Basin, Jordan Eastern basalt/sand desert grazed by Bedouin herds, adjacent to a wadi bed. Annual temperatures have an average low of 10°C, average maximum of 24.5°C, and average daily of 17.5°C, and annual precipitation is <100 mm. Remains were a single small adult *Bos taurus* carcass which died in the early summer, the bulk of which became mummified but with some elements dispersed.	All exposed bones reached WS 1 in less than six weeks. By one year later, multiple exposed elements had reached WS 2. By three years later, most exposed elements had reached WS 2, and some were WS 3; elements or portions thereof protected by desiccated soft tissue remained unweathered (WS 0). By seven years later, no elements had reached WS 4, but many were at WS 3. By 11 years later, most elements were at WS 3, only a few were still in WS 2, and some had reached WS 4.	Pokines and Ames (2015); and new data
Southern Arizona, USA Retrospective study of n = 189 forensic cases recovered from an arid environment, with variable microenvironments.	Sun bleaching detected as early as two months and was common by six months postmortem. Surface exfoliation (corresponding with an estimated WS 2) was found as early as four months, with metaphyseal loss (corresponding to at least WS 3) found at least by 5.5 years postmortem.	Galloway et al. (1989)
Tierra Blanca Mountains, California, USA The location receives under 8 cm of rain per year and has an average temperature range of 0–49°C. The surface was granitic sand. Carcasses from natural deaths of *Bos taurus* and *Equus caballus* were recorded.	Longitudinal weathering cracks could appear not long after deposition (possibly equivalent of WS 1). After one year, exposed bones were thoroughly bleached white. Transverse cracks appeared after two years. Exfoliation (equivalent to WS 2) began after four years. After 18 years, much exfoliation, cracking, and splintering (likely equivalent to WS 4) were present. Weathering likely equivalent to WS 5 noted by 31 years, with bones losing cohesion. Some bones in the area > 100 years old were in poor condition (WS 5) but still identifiable.	Miller (1975)

activity, a destructive process associated with warmer, moist environments (Bell et al. 1996).

In contrast to cooler, temperate climates, Behrensmeyer (1978) found skeletal elements to reach WS 1 or 2 within a year and WS 5 within 15 years of death in the Amboseli Basin, southern Kenya. Coe (1978) studied elephant (*Loxodonta africana*) remains in Tsavo (East) National Park, Kenya, and noted that most skeletal remains showed flaking of the outer surface (WS 2) within 4 years of exposure and estimated that bone survival intervals are at least 20 years. Isaac (1967) studied taphonomic changes of subadult goat (*Capra hircus*) and some additional cattle (*Bos taurus*) remains in southern Kenya and noted that advanced stages of weathering occurred after seven years. While this research predates the stage system of Behrensmeyer (1978), from the descriptions given (crumbled, cracked, friable, and fragile), it is clear that the majority of bones had reached at least WS 3 or more likely WS 4. Similarly, Tappen (1992, 1994) found that bone weathering in the savanna environment at Parc National des Virunga, Zaire, is comparable to the morphological changes and rates noted by Behrensmeyer (1978); however, in the same study, Tappen (1994) determined that bone weathering is significantly delayed and sometimes absent in the Ituri Rain Forest, Zaire. This can be attributed to the preservation of moisture content due to vegetation coverage and the wet environment and the protection from solar radiation. Kerbis Peterhans et al. (1993) also suggested that much less subaerial weathering occurs in rainforest environments than in savanna contexts based on observations made in Kibale Forest, Uganda. All chimpanzee (*Pan troglodytes*) skeletal elements that were located were reported to be in WS 0. The minimal degradation that was noted on this sample was attributed to mammalian carnivore and scavenger activity.

In contrast to the earlier findings, the findings reported by Andrews and Whybrow (2005) on the monitoring of a camel (*Camelus dromedarius*) skeleton for 15 years in a desert environment near Abu Dhabi, United Arab Emirates, indicated a much slower rate of weathering. Total exposure time was thought to be closer to 17 years, since the skeleton was disarticulated and the presence of soft tissue was minimal at the time of initial discovery, estimated at two years after the death of the camel. This arid environment lacks shading vegetation and experiences large daily temperature fluctuations. Under these environmental conditions, the potential for bone survival was expected to be low, but weathering was noted to be substantially slower when compared to weathering rates in tropical environments of similar latitudes. After eight years of exposure, most bones had barely reached WS 1; after 10 years, most bones were between WS 1 and WS 2; and after 15 years, only four bones out of the 15 that could be recorded at that time had reached WS 3. This pattern was observed for bones that were exposed on the surface for the entirety of the study, and bones that had become deeply buried showed little or no weathering after 15 years. This rate of weathering is in contrast to the findings (ongoing research of the senior author) at a location in the eastern basalt desert north of Azraq, Jordan (Pokines and Ames 2015). A small adult cattle carcass with an approximate time of death reported by its Bedouin owners was plotted for dispersal and assessed for rates of weathering for multiple years. This carcass is adjacent to a wadi, lying on a flat, sand surface with intermittent boulders and low scrub vegetation. Dispersal is primarily through domestic dogs, trampling by sheep/goat herds, and seasonal water transport of the few elements that made it into the wadi. While the presence of mummified soft tissue has protected a large portion of the central mass of skeletal remains (WS 0), all exposed bones reached WS 1 in less than six weeks. By one year after first analysis, multiple exposed elements had reached WS 2. By three years after deposition, most exposed elements had reached WS 2. By seven years postmortem, no elements had yet reached WS 4, but many were at WS 3. By 11 years postmortem, most elements had reached WS 3, only a few were still in WS 2, and some had reached WS 4; no elements had yet reached WS 5, although it is possible but not likely that some unrecovered elements did reach this stage and were not recovered in part due to their breakdown. This desert environment, too, is noted for its temperature fluctuations, which reach extremes of subzero to 45°C. Unlike the camel remains examined by Andrews and Whybrow (2005), no evidence exists that the cattle elements spent any time buried except for the few in the wadi. Andrews and Whybrow (2005) noted that their remains were at or near the bottom of a wadi, so the potential for temporary burial was much higher, and that some of the dispersed remains started off with desiccated skin attached.

Effects of Microenvironment

Given the prevalence for one portion of a bone to have reached a more advanced weathering stage than other portions of the same bone, despite the only differences in these portions being the underlying structure of the bone itself and the slight rotation toward more direct solar radiation while occupying an otherwise identical environment, it is clear that even minor variations in microhabitat can have a profound effect upon osseous weathering.

Tappen (1994) and Pokines (2009) noted very low rates of weathering in dense forest conditions where the remains were surface exposed but otherwise consistently protected from direct sunlight exposure. In the case of the latter study, no osseous weathering nor gnawing was detected on 10 sets of human remains that had been exposed on the surface in a rainforest environment in Papua New Guinea as the result of a WWII bomber crash, which was excavated 58 years later. The protective nature of partial wreckage, dense forest canopy, and the slow buildup of decaying leaf litter prevented any of the remains from reaching even WS 1, and the lack of significant large terrestrial scavengers in this environment limited the dispersal of remains. Most bone alteration in this environment was due to contact with acidic topsoil and infiltration and surface etching by plant roots.

Caves also may provide constant protection from direct sunlight exposure and contribute to bone preservation over a long period. Brain (1980) studied bovid bone accumulations in caves in various parts of southern Africa. Most bones that were located in a porcupine lair displayed signs of weathering, suggesting that the bones had weathered from surface exposure prior to being collected by porcupines. Porcupines show a preference for bleached, defatted bone. He noted that unless bones are defatted before collection in a cave, the bones will continue to exude grease indefinitely due to the protection from sun exposure. Pokines et al. (2011) studied taphonomic changes of megafauna and microfauna remains located within a large, open sinkhole in a semiarid environment near Wadi Zarqa Ma'in, Jordan. Very few elements had undergone significant weathering. The rate of weathering was slowed due to the lack of direct sunlight and whole carcass deposition, resulting in limited scavenging, slower decomposition rates, and mummification of the soft tissue.

Conversely, skeletal remains that are deposited in open grassland and receive minimal shade can progress through weathering stages at an accelerated rate. Fiorillo (1989), in an analysis of partial ungulate skeletons deposited in an open field in Nebraska, noted that the remains appeared to correspond to the same pattern and rate of weathering as observed by Behrensmeyer (1978) in southern Kenya. Similarly, Potmesil (2005) studied taphonomic changes to cattle bone in an open grassland in Nebraska and noted that the bones deteriorated at a constant rate, with each site representing a different weathering stage. The bones were exposed for approximately 13 years, five years, and three years and reached WS 4, WS 2, and WS 1, respectively. Ubelaker and Sperber (1988) noted that weathering can be highly localized on a skeletal element where sun exposure strikes only that part of the element in an otherwise protected artificial environment. High temperatures resulting from direct sun exposure accelerate the rate of collagen loss, leading to a change in bone matrix organization and ultimately resulting in a mineral "ghost" (Collins et al. 2002).

Microenvironment also may affect how quickly skeletal remains become partially or completely buried after deposition, influencing the exposure time and ultimately hindering weathering processes (Andrews 1995; Behrensmeyer 1978, 1983; Miller 2009; Ross and Cunningham 2011; Serjeantson 1991; Shipman 1981; Tappen and Peske 1970; Todisco and Monchot 2008). Well-preserved buried bones may indicate rapid burial, whereas highly weathered buried bones imply a longer exposure length prior to burial (Todisco and Monchot 2008). Miller (2009) determined the proportion of buried bones to surface-deposited bones for four different microenvironments in Yellowstone National Park, USA. The bone assemblages located in grasslands displayed the slowest rates of burial, followed by river margins, forests, and lake margins. These differences are likely due in most part to the degree to which decaying leaf litter builds up in these habitats. In turn, the burial environment will affect skeletal preservation based on soil pH and water fluctuations. For example, waterlogged soils are more likely to preserve organic materials than well-drained soils, and highly acidic environments will increase the rate of degradation (Crow 2008; Gordon and Buikstra 1981). Hill (1980) noted that buffalo skeletal remains buried in a mud wallow in southwest Uganda were found in near-perfect condition after 52 months since death. Furthermore, Conard et al. (2008) studied a faunal accumulation in the Geelbek Dunes of South Africa, which is continuously affected by cycles of open-air exposure and burial. This cycle subjects the elements to daily heating-cooling and wetting-drying, leading to the more rapid destruction of cortical bone and the survival of more porous bone. Although the extent of weathering is related to the time of exposure, weathering progresses at different rates in various microenvironments, thus making it more difficult to determine a standard rate at which weathering stages occur (Shipman 1981:115). General patterns among various macroenvironments have been recognized in relation to the rate of weathering (Table 11.4), with colder environments and less solar radiation acting to slow the rate of weathering and warmer, arid environments with high solar radiation accelerating the rate of weathering. However, contradicting results exist, and microenvironments can also significantly alter this rate, indicating that more research is still needed.

Confusion with Other Taphonomic Effects

Weathering can be mistaken for the gross effects of taphonomic forces that cause whitening of bone, including calcination from prolonged, intense thermal exposure or boiling (Chapter 14) and bleaching from submersion in saltwater (Chapter 7). Macroscopic examination of weathered bone should reveal clear differences between these other common alterations. The analyst is cautioned that weathering is often found in conjunction with other taphonomic alterations.

Distinguishing Weathering from Calcination

Calcination of bone as a result of extreme thermal alteration (Chapter 14) can mimic superficially the effects of advanced weathering. Both processes turn bone various shades of white/gray, and both processes crack bone. Upon close visual inspection, the two taphonomic effects can be distinguished. The orientation of weathering cracks on articular surfaces may follow a pattern similar to that observed on dry lake beds, where the drying clay forms multisided shapes. The orientation of cracks elsewhere, however, typically follows the long axis of the bone along the main orientation of the osteons (Tappen 1969, 1976; Tappen and Peske 1970). Weathering cracking is accompanied by cortical exfoliation at lower stages and deeper flaking at more advanced stages. The appearance of these flakes is far more ragged than the fragments formed by thermal alteration/calcination. In addition, the surfaces of calcined bone present a much smoother appearance around these cracks than the surfaces of weathered bone. Crack orientation also follows multiple paths and often is perpendicular to the long axis of a bone. Calcination also often affects only a portion of a bone or bone fragment, with zones of carbonization deeper or adjacent. Unburned bone also may be adjacent to these areas of carbonization. Weathering does not cause bone to turn black, and inner portions of a bone where sun bleaching has not penetrated may retain the original (beige) color (Chapter 12). Finally, calcination also can be accompanied by bone warping and fine bone ash, neither of which are caused nor mimicked by weathering.

Distinguishing Weathering from Saltwater Immersion

Bone in marine environments undergoes bleaching that may mimic the appearance of sun bleaching (Ubelaker 1997). Similarly, bones removed from marine environments may later crack as a part of the drying process that may include the formation of salt crystals forcing the bone apart. The overall patterns of taphonomic alteration, however, are distinguishable upon close examination. Except in rare cases, saltwater bleaching affects all surfaces of a bone relatively equally (Chapter 7). This is because the ions in the liquid medium can penetrate all surfaces from all angles. In contrast, the changes that a weathered bone undergoes, including sun bleaching, is rarely uniform, and the portion of the bone facing the ground surface often can lag even three weathering stages behind the most exposed upper surface. Marine-altered bones also tend to become rounded from the abrasion of sand particles, selectively removing more exposed portions of the element (Fisher 1995; Isaac 1967). Weathering itself produces no such rounding effect, although later abrasion of a previously weathered bone might (Fernández-Jalvo and Andrews 2003). Marine-altered bones, of course, are often discovered after their deposition in beach contexts where they subsequently may weather, thus combining characteristics of both. Previous rounding may be detected on subsequently weathered bone, and weathering will likely be more advanced on the uppermost exposed surfaces. Salt cracking, however, may proceed equally in all directions.

Conclusions

Osseous subaerial weathering is a progressive process that follows a pattern of linear cracking and flaking of the cortical surface, followed by formation of a rough fibrous texture and eventual loss of bone structure (Behrensmeyer 1978). The analysis of bone weathering is particularly important to the field of forensic anthropology, with the potential to contribute to PMI estimations for cases involving advanced stages of decomposition (i.e., skeletonization followed by skeletal breakdown). The rate of weathering is highly variable among different climates (e.g., temperate deciduous forest, semiarid equatorial savanna, or tundra) and various microenvironments within that climatic zone (e.g., patches of tree, brush, wetland, or grass cover within a temperate deciduous forest), and all environmental aspects must be considered when assessing PMI. This variation has been little researched and demonstrates the need for further investigation of bone weathering across different regions. It is also clear that weathering of nonhuman (largely plexiform) bone may differ significantly in patterning and timing from adult human (largely lamellar) bone, and future forensic research must include the latter.

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References

Andrews, P. (1995) Experiments in taphonomy. *Journal of Archaeological Science* 22(2):147–153.

Andrews, P., and M. Armour-Chelu (1998) Taphonomic observations on a surface bone assemblage in a temperate environment. *Bulletin de la Société Géologique de France* 169(3):433–442.

Andrews, P., and J. Cook (1985) Natural modifications to bones in a temperate setting. *Man* 20(4):675–691.

Andrews, P., and P. Whybrow (2005) Taphonomic observations on a camel skeleton in a desert environment in Abu Dhabi. *Palaeontologica Electronica* 8(23A):1–17.

Banfield, J. F., W. W. Barker, S. A. Welch, and A. Taunton (1999) Biological impact on mineral dissolution: Application of the lichen model to understanding mineral weathering in the rhizosphere. *Proceedings of the National Academy of Sciences of the United States of America* 96(7):3404–3411.

Beary, M. O. (2005) *Estimation of Bone Exposure Duration through the Use of Spectrophotometric Analysis of Surface Bleaching and Its Application in Forensic Taphonomy*. M.S. Thesis, Mercyhurst College, Erie, PA.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Palaeobiology* 4(2):150–162.

Behrensmeyer, A. K. (1983) Patterns of natural bone distribution on recent land surfaces: Implications for archaeological site formation. In *Animals and Archaeology: 1. Hunters and Their Prey* ed. by J. Clutton-Brock and C. Grigson, pp. 93–106. British Archaeological Reports International Series 163, Oxford.

Behrensmeyer, A. K., and J. H. Miller (2012) Building links between ecology and paleontology using taphonomic studies of recent vertebrate communities. In *Paleontology in Ecology and Conservation* ed. J. Louys, pp. 69–91. Springer-Verlag, Berlin.

Bell, L. S., M. F. Skinner, and S. J. Jones (1996) The speed of post mortem change to the human skeleton and its taphonomic significance. *Forensic Science International* 82:129–140.

Benedict, J. B. (2009) A review of lichenometric dating and its applications to archaeology. *American Antiquity* 74(1):143–172.

Bertran, P., C. Beauval, S. Boulogne, M. Brenet, S. Costamagno, T. Feuillet, V. Laroulandie, A. Lenoble, P. Malaurent, and J. B. Mallye (2015) Experimental archaeology in a midlatitude periglacial context: Insight into site formation and taphonomic processes. *Journal of Archaeological Science* 57:283–301.

Brain, C. K. (1967) Bone weathering and the problem of bone pseudo-tools. *South African Journal of Science* 63(3):97–99.

Brain, C. K. (1980) Some criteria for the recognition of bone-collecting agencies in African caves. In *Fossils in the Making* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 107–130. University of Chicago Press, Chicago.

Brain, C. K. (1981) *The Hunters or the Hunted? An Introduction to African Cave Taphonomy.* University of Chicago Press, Chicago.

Buckland-Wright, J. C. (1977) Microradiographic and histological examination of the split-line formation in bone. *Journal of Anatomy* 124(1):193–203.

Buikstra, J. E., and D. H. Ubelaker (eds.) (1994) *Standards for Data Collection from Human Skeletal Remains.* Arkansas Archeological Survey Research Series No. 44, Fayetteville, AR.

Buikstra, J. E., and L. Goldstein (1973) *The Perrins Ledge Crematory.* Illinois State Museum, Report of Investigations No. 28, Springfield, IL.

Christensen, A. M., L. S. Larsen, and B. F. Spatola (2019) A case of split-line research specimens submitted for forensic anthropological analysis. *Forensic Anthropology* 2(3):189–192.

Coe, M. (1978) The decomposition of elephant carcasses in the Tsavo (East) National Park, Kenya. *Journal of Arid Environments* 1(1):71–86.

Collins, M. J., C. M. Nielsen-Marsh, J. Hiller, C. I. Smith, J. P. Roberts, T. J. Wess, T. J. Csapo, A. R. Millard, R. V. Priyodich, and G. Turner-Walker (2002) The survival of the organic matter of bone: A review. *Archaeometry* 44(3):383–394.

Conard, N. J., S. J. Walker, and A. W. Kandel (2008) How heating and cooling and wetting and drying can destroy dense faunal elements and lead to differential preservation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 266:459–469.

Cox, B. N., and Q. Yang (2007) Cohesive zone models of localization and fracture in bone. *Engineering Fracture Mechanics* 74:1079–1092.

Crow, P. (2008) Mineral weathering in forest soils and its relevance to the preservation of the buried archaeological resource. *Journal of Archaeological Science* 35(8):2262–2273.

Currey, J. D. (2002) *Bones: Structure and Mechanics* (2nd ed.). Princeton University Press, Princeton, NJ.

Cutler, A. H., A. K. Behrensmeyer, and R. E. Chapman (1999) Environmental information in a recent bone assemblage: Roles of taphonomic processes and ecological change. *Palaeogeography, Palaeoclimatology, Palaeoecology* 149:359–372.

Doblaré, M., J. M. García, and M. J. Gómez (2004) Modelling bone tissue fracture and healing: A review. *Engineering Fracture Mechanics* 71(13–14):1809–1840.

Doehne, E. (2002) Salt weathering: A selective review. *Geological Society Special Publication: Natural Stone, Weathering Phenomena, Conservation Strategies and Case Studies* 205(1):51–64.

Faith, J. T., and A. K. Behrensmeyer (2006) Changing patterns of carnivore modification in a landscape bone assemblage, Amboseli Park, Kenya. *Journal of Archaeological Science* 33(12):1718–1733.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Fiorillo, A. R. (1989) An experimental study of trampling: Implications for the fossil record. In *Bone Modification* ed. by R. Bonnichsen and M. Sorg, pp. 61–72. Center for the Study of the First Americans, Orono, ME.

Fiorillo, A. R. (1995) Possible influence of low temperature on bone weathering in Curecanti National Recreation Area, southwest Colorado. *Current Research in the Pleistocene* 12:69–71.

Fisher, J. W. (1995) Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory* 2(1):7–68.

Galloway, A. (ed.) (1999) *Broken Bones: Anthropological Analysis of Blunt Force Trauma*. Charles C Thomas, Springfield, IL.

Galloway, A., W. H. Birkby, A. M. Jones, T. E. Henry, and B. O. Parks (1989) Decay rates of human remains in an arid environment. *Journal of Forensic Sciences* 34(3):607–616.

Geberth, V. J. (2006) *Practical Homicide Investigation* (4th ed.). CRC Press, Boca Raton, FL.

Gifford, D. P. (1984) Taphonomic specimens, Lake Turkana. *National Geographic Society Research Reports* 17:419–428.

Gordon, C. G., and J. E. Buikstra (1981) Soil pH, bone preservation, and sampling bias at mortuary sites. *American Antiquity* 46(3):566–571.

Guadelli, J.-L. (2008) La gélifraction des restes fauniques. Expérimentation et transfert au fossile. *Annales de Paléontologie* 94:121–165.

Guadelli, J.-L. (2015) La gélifraction des restes fauniques. Du laboratoire au terrain. In *Messages d'Os: Archéométrie du Squelette Animal et Humain* ed. by M. Balasse, J. P. Brugal, Y. Dauphin, E. M. Geigl, C. Oberlin, and I. Reiche, pp. 177–186. Editions des Archives Contemporaines, Paris.

Guadelli, J.-L., and J.-C. Ozouf (1994) Étude expérimentales de l'action du gel sur les restes fauniques: Premiers résultats. *Artefacts* 9:47–56.

Haefner, J. N., J. R. Wallace, and R. W. Merritt (2004) Pig decomposition in lotic aquatic systems: The potential use of algal growth in establishing a postmortem submersion interval (PMSI). *Journal of Forensic Sciences* 49(2):330–336.

Hall, K. (1999) The role of thermal stress fatigue in the breakdown of rock in cold regions. *Geomorphology* 31(1-4):47–63.

Hall, K., and C. E. Thorn (2011) The historical legacy of spatial scales in freeze-thaw weathering: Misrepresentation and resulting misdirection. *Geomorphology* 130(1–2):83–90.

Hall, K., and C. E. Thorn (2014) Thermal fatigue and thermal shock in bedrock: An attempt to unravel the geomorphic processes and products. *Geomorphology* 206:1–13.

Hare, E. P. (1974) Amino acid dating of bone—The influence of water. *Carnegie Institute of Washington Yearbook* 73:576–581.

Hedges, R. E. M., A. R. Millard, and A. W. G. Pike (1995) Measurements and relationships of diagenetic alteration of bone from three archaeological sites. *Journal of Archaeological Science* 22(2):201–211.

Hill, A. (1976) On carnivore and weathering damage to bone. *Current Anthropology* 17(2):335–336.

Hill, A. (1980) Early postmortem damage to the remains of some contemporary East African mammals. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 131–152. University of Chicago Press, Chicago.

Hillier, M. L., and L. S. Bell (2007) Differentiating human bone from animal bone: A review of histological methods. *Journal of Forensic Sciences* 52(2):249–263.

Isaac, G. L. (1967) Towards the interpretation of occupation debris: Some experiments and observations. *The Kroeber Anthropological Society Papers* 37:31–57.

Janjua, M. A., and T. L. Rogers (2008) Bone weathering patterns of metatarsal v. femur and the postmortem interval in Southern Ontario. *Forensic Science International* 178:16–23.

Johnson, J. S. (1998) Soluble salts and deterioration of archeological materials. *Conserve O Gram National Park Service US* 6/5(August):1–4.

Junod, C. A. (2013) *Subaerial Bone Weathering and Other Taphonomic Changes in a Temperate Climate*. M.S. Thesis, Boston University School of Medicine, Boston.

Kerbis Peterhans, J., R. W. Wrangham, M. L. Carter, and M. D. Hauser (1993) A contribution to tropical rainforest taphonomy: Retrieval and documentation of chimpanzee remains from Kibale Forest, Uganda. *Journal of Human Evolution* 25(6):485–514.

Kerbis Peterhans, J. C. (1990) *The Roles of Porcupines, Leopards, and Hyenas in Ungulate Carcass Dispersal: Implications for Paleoanthropology*. Ph.D. Dissertation, Department of Anthropology, University of Chicago, Chicago.

Kollmorgen Instruments Corporation (1994) *Munsell® Soil Color Charts* (rev. ed.). Kollmorgen Instruments Corporation, New Windsor, NY.

Lyman, R. L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

Lyman, R. L., and G. L. Fox (1989) A critical evaluation of bone weathering data as an indication of bone assemblage formation. *Journal of Archaeological Science* 16(3):293–317.

Lyman, R. L., and G. L. Fox (1997) A critical evaluation of bone weathering as an indication of bone assemblage formation. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 223–247. CRC Press, Boca Raton, FL.

Madgwick, R., and J. Mulville (2012) Investigating variation in the prevalence of weathering in faunal assemblages in the UK: A multivariate statistical approach. *International Journal of Osteoarchaeology* 22:509–522.

Maijanen, H., R. J. Wilson-Taylor, and L. Meadows Jantz (2016) Storm-related postmortem damage to skeletal remains. *Journal of Forensic Sciences* 61(3):823–827.

Mallye, J.-B., S. Costamagno, V. Laroulandie, and C. Beauval (2009) Impacts des processus périglaciaires sur la préservation des ossements. *Les Nouvelles de l'Archéologie* 118:26–31.

Matsuoka, N. (1995) Rock weathering and landform development in the Sør Rondane Mountains, Antarctica. *Geomorphology* 12(4):323–339.

Matsuoka, N. (1996) Soil moisture variability in relation to diurnal frost heaving on Japanese high mountain slopes. *Permafrost and Periglacial Processes* 7(2):139–151.

Matsuoka, N., and J. Merton (2008) Frost weathering: Recent advances and future directions. *Permafrost and Periglacial Processes* 19(2):195–210.

McGee, M. E., K. W. Magic, D. L. Miller, A. J. Maki, and S. W. Donahue (2007) Black bear femoral porosity decreases and mechanical properties increase with age despite annual periods of disuse (hibernation). *Engineering Fracture Mechanics* 74(12):1942–1952.

Megyesi, M. S., S. P. Nawrocki, and N. H. Haskell (2005) Using accumulated degree-days to estimate the postmortem interval from decomposed human remains. *Journal of Forensic Sciences* 52(3):618–626.

Micozzi, M. S. (1991) *Postmortem Change in Human and Animal Remains*. Charles C Thomas, Springfield, IL.

Miller, J. H. (2009) *The Large-Mammal Death Assemblage of Yellowstone National Park: Historical Ecology, Conservation Biology, Paleoecology*. Ph.D. Dissertation, University of Chicago, Chicago.

Miller, J. H. (2011) Ghosts of Yellowstone: Multi-decadal histories of wildlife populations captured by bones on a modern landscape. *PLoS ONE* 6(3):e18057. DOI: 10.1371/journal.pone.0018057.

Miller, J. H. (2012) The spatial fidelity of skeletal remains: Elk wintering and calving grounds revealed by bones on the Yellowstone landscape. *Ecology* 93(11):2474–2482.

Miller, J. H., P. Druckenmiller, and V. Bahn (2013) Antlers of the Arctic Refuge: Capturing multigenerational patterns of calving ground use from bones on the landscape. *Proceedings of the Royal Society B* 280:20130275. DOI: 10.1098/rspb.2013.0275.

Miller, G. J. (1975) A study of cuts, grooves, and other marks on recent and fossil bones. II. Weathering cracks, fractures, splinters, and other similar natural phenomena. In *Lithic Technology: Making and Using Stone Tools* ed. by E. H. Swanson, Jr., pp. 211–226. Aldine, Chicago.

Morris, P. J. (2013) *Bone Weathering in the Mediterranean Climate of the Northern California Foothills: A Taphonomy Study*. M.A. Thesis, California State University, Sacramento, CA.

Morris, Z. H. (2007) *Quantitative and Spatial Analysis of the Microscopic Bone Structures of Deer* (Odocoileus virginianus), *Dog* (Canis familiaris), *and Pig* (Sus scrofa domesticus). M.A. Thesis, Louisiana State University, Shreveport, LA.

Mulhern, D. M., and D. H. Ubelaker (2001) Differences in osteon banding between human and nonhuman bone. *Journal of Forensic Sciences* 46(2):220–222.

Nielsen-Marsh, C. M., A. M. Gernaey, G. Turner-Walker, R. E. M. Hedges, A. W. G. Pike, and M. J. C. Collins (2000) The chemical degradation of bone. In *Human Osteology in Archaeology and Forensic Science* ed. by M. Cox and S. Mays, pp. 439–454. Greenwich Medical Media, London.

Ouacha, H., A. Ben Moussa, and J. Simao (2013) The salt crystallization weathering of building rocks of the archaeological sites calcarenites of north-western Morocco (Lixus, Banasa and Thamusida). *European Scientific Journal* 9(18):282–290.

Pal, S., and S. Saha (1989) Coefficient of thermal expansion of bone. In *Biomechanics* ed. by K. B. Sahay and R. K. Saxena, pp. 52–60. Wiley, New York.

Pate, F. D., and J. T. Hutton (1988) The use of soil chemistry data to address post-mortem diagenesis in bone mineral. *Journal of Archaeological Science* 15(6):729–739.

Pate, F. D., J. T. Hutton, and K. Norrish (1989) Ionic exchange between soil solution and bone: Toward a predictive model. *Applied Geochemistry* 4(3):303–316.

Pietruszczak, S., K. Gdela, C. E. Webber, and D. Inglis (2007) On the assessment of brittle-elastic cortical bone fracture in the distal radius. *Engineering Fracture Mechanics* 74(12):1917–1927.

Pokines, J. T. (2009) Forensic recoveries of U.S. war dead and the effects of taphonomy and other site-altering processes. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 141–154. Prentice Hall, Upper Saddle River, NJ.

Pokines, J. T. (2015) Identification of nonhuman remains received in a medical examiner setting. *Journal of Forensic Identification* 65(3):223–246.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T. (2018) Two cases of dendrochronology used to corroborate a forensic postmortem interval. *Journal of Forensic Identification* 68(4):457–465.

Pokines, J. T., and C. J. H. Ames (2015) Weathering and dispersal of a cattle (*Bos taurus*) carcass in the desert of eastern Jordan over a six-year interval. *Journal of Taphonomy* 13(1):17–31.

Pokines, J. T., C. J. Eck, and M. E. Sharpe (2017) Sources of skeletal remains at a chief medical examiner's office: Who finds the bones? *Journal of Forensic Identification* 67(2):278–299.

Pokines, J. T., A. Nowell, M. S. Bisson, C. E. Cordova, and C. J. H. Ames (2011) The functioning of a natural faunal trap in a semi-arid environment: Preliminary investigations of WZM-1, a limestone sinkhole site near Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan. *Journal of Taphonomy* 9(2):89–115.

Pokines, J. T., K. Faillace, J. Berger, D. Pirtle, M. Sharpe, A. Curtis, K. Lombardi, and J. Admans (2018) The effects of repeated wet-dry cycles as a component of bone weathering. *Journal of Archaeological Science: Reports* 17:433–441.

Pokines, J. T., R. E. King, D. D. Graham, A. K. Costello, D. M. Adams, J. M. Pendray, K. Rao, and D. Siwek (2016a) The effects of experimental freeze-thaw cycles to bone as a component of subaerial weathering. *Journal of Archaeological Science: Reports* 6:594–602.

Pokines, J. T., D. P. Zinni, and K. Crowley (2016b) Taphonomic patterning of cemetery remains received at the Office of the Chief Medical Examiner, Boston, Massachusetts. *Journal of Forensic Sciences* 61(S1):S71–S81.

Potmesil, M. (2005) Bone dispersion, weathering, and scavenging of cattle bones. *Nebraska Anthropologist, Paper 6*. [Available online: http://digitalcommons.unl.edu/nebanthro/6.]

Prassack, K. A. (2011) The effect of weathering on bird bone survivorship in modern and fossil saline-alkaline lake environments. *Paleobiology* 37(4):633–654.

Purdy, B. A., and D. E. Clark (1987) Weathering of inorganic materials: Dating and other applications. *Advances in Archaeological Method and Theory* 11:211–253.

Pyle, J. A. (2016) *Using Solar Radiation as a Means for Understanding Skeletal Decomposition Through Physical Changes Caused by Bone Weathering*. M.S. Thesis, Texas State University, San Marcos, TX.

Rodriguez-Navarro, C., and E. Doehne (1999) Salt weathering: Influence of evaporation rate, supersaturation and crystallization pattern. *Earth Surface Processes and Landforms* 24:191–209.

Ross, A. H., and S. L. Cunningham (2011) Time-since-death and bone weathering in a tropical environment. *Forensic Science International* 204:126–133.

Roze, U. (2009) *The North American Porcupine* (2nd ed.). Cornell University Press, Ithaca, NY.

Schultz, J. J., M. M. Hawkins, and A. T. Mitchell (2018) Skeletal weathering in central Florida: A preliminary approach for developing a scoring protocol to estimate time since death. *Forensic Science International* 290:85–93.

Schütz, W. (1996) A history of fatigue. *Engineering Fracture Mechanics* 54(2):263–300.

Serjeantson, D. (1991) Rid grasse of bones: A taphonomical study of bones from midden deposits at the Neolithic and Bronze Age site at Runnymede, Surrey, England. *International Journal of Osteoarchaeology* 1:73–89.

Shipman, P. (1981) *Life History of a Fossil*. Harvard University Press, Cambridge, MA.

Sillen, A. (1989) Diagenesis of the inorganic phase of the cortical bone. In *The Chemistry of Prehistoric Bone* ed. by T. D. Price, pp. 211–229. Cambridge University Press, Cambridge.

Skedros, J. G., J. L. Holmes, E. G. Vajda, and R. L. Bloebaum (2005) Cement lines of secondary osteons in human bone are not mineral-deficient: New data in a historical perspective. *The Anatomical Record Part A* 286A:781–803.

Smith, C. I., O. E. Craig, R. V. Prigodich, C. M. Nielsen-Marsh, M. M. E. Jans, C. Vermeer, and M. J. Collins (2005) Diagenesis and survival of osteocalcin in archaeological bone. *Journal of Archaeological Science* 32(1):105–113.

Stiner, M. C., S. L. Kuhn, and O. Bar-Yosef (1995) Differential burning, recrystallization, and fragmentation of archaeological bone. *Journal of Archaeological Science* 22(2):223–237.

Stokes, S., N. Márquez-Grant, and C. Greenwood (2020) Establishing a minimum PMI for bone sun bleaching in a UK environment with a controlled desert-simulated comparison. *International Journal of Legal Medicine* 134(5):2297–2306.

Stover, S. M., R. P. Pool, B. Martin, and J. P. Morgan (1992) Histological features of the dorsal cortex of the third metacarpal bone mid-diaphysis during postnatal growth in thoroughbred horses. *Journal of Anatomy* 181(3):455–469.

Tappen, M. (1992) *Taphonomy of a Central African Savanna: Natural Bone Deposition in Parc National des Virunga, Zaire*. Ph.D. Dissertation, Harvard University, Cambridge, MA.

Tappen, M. (1994) Bone weathering in the tropical rain forest. *Journal of Archaeological Science* 21(5):667–673.

Tappen, M. (1995) Savanna ecology and natural bone deposition: Implications for early hominid site formation, hunting, and scavenging. *Current Anthropology* 36(2):223–260.

Tappen, N. C. (1969) The relationship of weathering cracks to split-line orientation in bone. *American Journal of Physical Anthropology* 31(2):191–197.

Tappen, N. C. (1976) Advanced weathering cracks as an improvement on split-line preparations for analysis of structural orientation in compact bone. *American Journal of Physical Anthropology* 44(2):373–377.

Tappen, N. C., and R. Peske (1970) Weathering cracks and split-line patterns in archaeological bone. *American Antiquity* 35(3):383–386.

Tersigni, M. A. (2007) Frozen human bone: A microscopic investigation. *Journal of Forensic Sciences* 52(1):16–20.

Texier, J. P., P. Bertran, J. P. Coutard, B. Francou, P. Gabert, J. L. Guadelli, J. C. Ozouf, H. Plisson, J. P. Raynal, and D. Vivent (1998) TRANSIT, an experimental archaeological program in periglacial environment: Problem, methodology, first results. *Geoarchaeology* 13(5):433–473.

Thurner, P. J., B. Erickson, R. Jungmann, Z. Schriock, J. C. Weaver, G. E. Fantner, G. Schitter, D. E. Morse, and P. K. Hansma (2007) High-speed photography of compressed human trabecular bone correlates whitening to microscopic damage. *Engineering Fracture Mechanics* 74(12):1928–1941.

Todisco, D., and H. Monchot (2008) Bone weathering in a peri-glacial environment: The Tayara Site (KbFk-7), Qikirtaq Island, Nunavik (Canada). *Arctic* 61(1):87–101.

Tomar, V. (2009) Insights into the effects of tensile and compressive loadings on microstructure dependent fracture of trabecular bone. *Engineering Fracture Mechanics* 76(7):884–897.

Toots, H. (1965) Sequence of disarticulation in mammalian skeletons. *Contributions to Geology* 4:37–39.

Trueman, C. N. G., A. K. Behrensmeyer, N. Tuross, and S. Weiner (2004) Mineralogical and compositional changes in bones exposed on soil surfaces in Amboseli National Park, Kenya: Diagenetic mechanisms and the role of sediment pore fluids. *Journal of Archaeological Science* 31(6):721–739.

Turner, C. H., T. Wang, and D. B. Burr (2001) Shear strength and fatigue properties of human cortical bone determined from pure shear tests. *Calcified Tissue International* 69(6):373–378.

Turner-Walker, G. (2008) The chemical and microbial degradation of bones and teeth. In *Advances in Human Palaeopathology* ed. by R. Pinhasi and S. Mays, pp. 3–29. Wiley, Chichester, UK.

Turpin, C. (2017) The micro-taphonomy of cold: Differential microcracking in response to experimental cold-stresses. *Journal of Forensic Sciences* 62(5):1134–1139.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–90. CRC Press, Boca Raton, FL.

Ubelaker, D. H., and N. D. Sperber (1988) Alterations in human bones and teeth as a result of restricted sun exposure and contact with corrosive agents. *Journal of Forensic Sciences* 33(2):540–548.

Walderhaug, O. (1998) Chemical weathering at rock art sites in western Norway: Which mechanisms are active and how can they be retarded? *Journal of Archaeological Science* 25(8):789–800.

Weiner, S., and H. D. Wagner (1998) The material bone: Structure-mechanical function relations. *Annual Review of Materials Science* 28:271–298.

Western, D., and A. K. Behrensmeyer (2009) Bone assemblages track animal community structure over 40 years in an African savanna ecosystem. *Science* 324(5930):1061–1064.

White, E. M., and L. A. Hannus (1983) Chemical weathering of bone in archaeological soils. *American Antiquity* 48(2):316–322.

Willey, P., and A. Heilman (1987) Estimating time since death using plant roots and stems. *Journal of Forensic Sciences* 32(5):1264–1270.

Yavuz, H. (2011) Effect of freeze-thaw and thermal shock weathering on the physical and mechanical properties of an andesite stone. *Bulletin of Engineering Geology and the Environment* 70(2):187–192.

Identifying the Origin of Taphonomic Bone Staining and Color Changes in Forensic Contexts

12

JOHN J. SCHULTZ
TOSHA L. DUPRAS

Contents

> The progress of science, like an ancient desert trail, is strewn with the bleached skeletons of discarded theories, doctrines, and axioms which seemed to possess eternal life.
>
> **—Arthur Koestler**

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Introduction

A component of forensic skeletal analysis is to identify various postmortem modifications and to reconstruct the depositional history of the remains. Bone staining is a ubiquitous taphonomic modification, and various color changes including organic staining (Pollock et al. 2018) and sun bleaching (Schultz et al. 2018) can be exhibited on bones within a limited time frame based on the depositional environment and how quickly skeletonization occurs. Describing any color changes associated with bones is important to the analytical process, as it may provide clues when reconstructing the postdepositional environment of skeletal remains. The purpose of this chapter is to present examples of bone staining and color changes and to discuss the causative taphonomic agents such as chemicals, natural bleaching, organics, metals, and soil, that are more commonly encountered by the forensic anthropologist.

To understand how bone color changes, it is important to be familiar with the normal color of unstained bone when describing staining noted on bones. Normal fresh bone devoid of flesh has been described as having a yellowish-white to yellowish-brown color (Figure 12.1a through c) due to the retention of lipids and other fluids (Byers 2008; Schafer

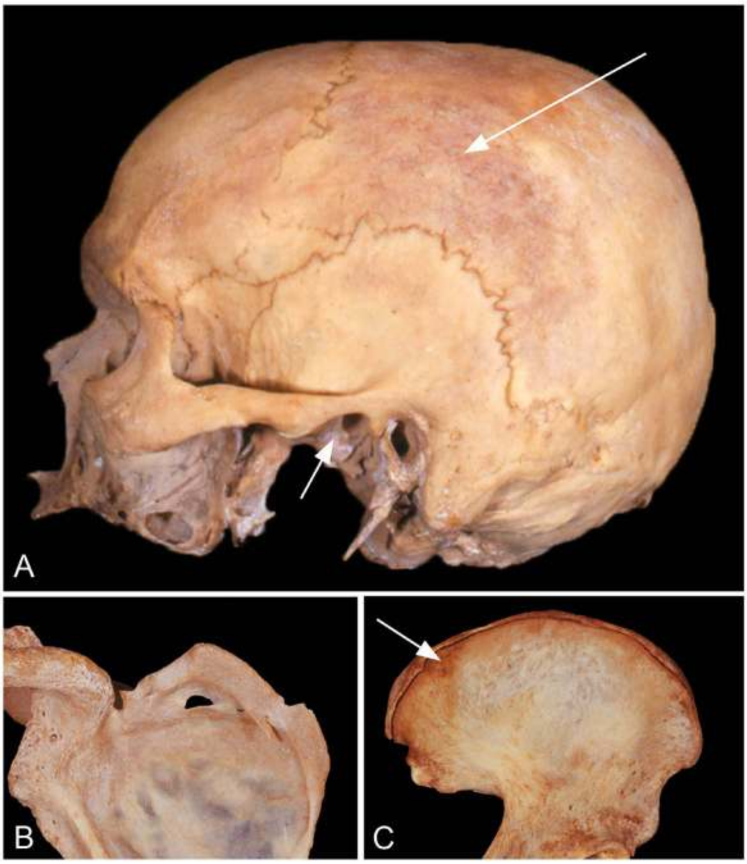

Figure 12.1 Examples of natural bone coloration reflecting the presence of lipids: (a) cranium exhibiting examples of hemolysis (top arrow) and adipocere (bottom arrow); (b) scapula with tissue and lipid retention; and (c) ilium with darker coloration representing concentrated areas of lipid retention (arrow).

2001). Interestingly, fresh skulls with a bright yellow color have been associated with individuals who suffered from diabetes (Gruspier 1999). While Schafer (2001) did not find an increased yellow coloration in a small sample of fresh diabetic skulls compared to a sample of non-diabetic skulls, he did find a correlation of increased yellow hue with increased age at death.

A suggested method to document bone color entails using a Munsell® Color chart (e.g., Cain 2005; Pollock et al. 2018; Schultz et al. 2018), which identifies color based on three dimensions: value, hue, and chroma. The color of bone will change during the decomposition process and when the bone is completely dry. In a controlled study designed to analyze the early postmortem interval (PMI) up to 8 weeks, Huculak and Rogers (2009) concluded that color changes occurring on various skeletal elements that were either on the ground surface or buried were the result of soil, sun, hemolysis, decomposition, and fungi. During decomposition, bones can display areas of dark reddish-brown coloration due to hemolysis, or the breakdown of red blood cells (Figure 12.1a), and a dark reddish-gray coloration due to decomposition staining (Huculak and Rogers 2009). When bones become dry during the postmortem period, the yellowish hue may change to an ivory or off-white color (Figure 12.1b) (Byers 2008). There are, however, many taphonomic and environmental conditions which can cause a myriad of color changes to bone. In addition, bones recovered from outdoor environments often display differential patterns of staining that represent multiple taphonomic processes (Figures 12.2a and b). At the same time, it is important to recognize that different taphonomic processes can cause similar color changes to bone. For example, a variety of taphonomic processes can result in a white coloration to bone such as adipocere remnants, burning, sun bleaching, adhered concretions, and commercial preparation of skeletal remains for teaching (see "Natural Bleaching and Chemical Staining" section and "Mineral Precipitates and Other Encrustations" section, below).

Natural Bleaching and Chemical Staining

Sun Bleaching

In some instances, bones may appear to be a variant of the color white, from gray to brilliant white. Ultraviolet radiation from sunlight will cause natural bleaching of exposed bones (see Chapter 11, this volume). Solar UV radiation can be responsible for the degradation and/or decomposition of many organic compounds, and it does so by breaking chemical bonds during photolytic and photo-oxidative reactions (Zayat et al. 2007). In bone, UV radiation assists in breaking down the organic components that contribute to the color of bone such as blood, lipids, and proteins. Eventually, after substantial exposure to UV radiation and other environmental conditions, all that may remain is the mineral portion of bone, hydroxyapatite, which is naturally white in color.

The color of bleached bones will depend on the length of exposure, and the longer the exposure, the more bleached the bones can become. After significant exposure bones may appear a brilliant white color (Beary 2005; Haglund et al. 2002; Schultz et al. 2018; Ubelaker 1997). Several authors noted changes in bone color due to sun bleaching (e.g., Calce and Rogers 2007; Galloway et al. 1989; Huculak and Rogers 2009; Quatrehomme and İşcan 1997; Schultz et al. 2018). Figure 12.3a through c compares the effects of sun bleaching on bones from different contexts. Figure 12.3a shows a left femur from an archaeological context in Egypt in which the bone had been exposed on the surface for over a year. In addition to

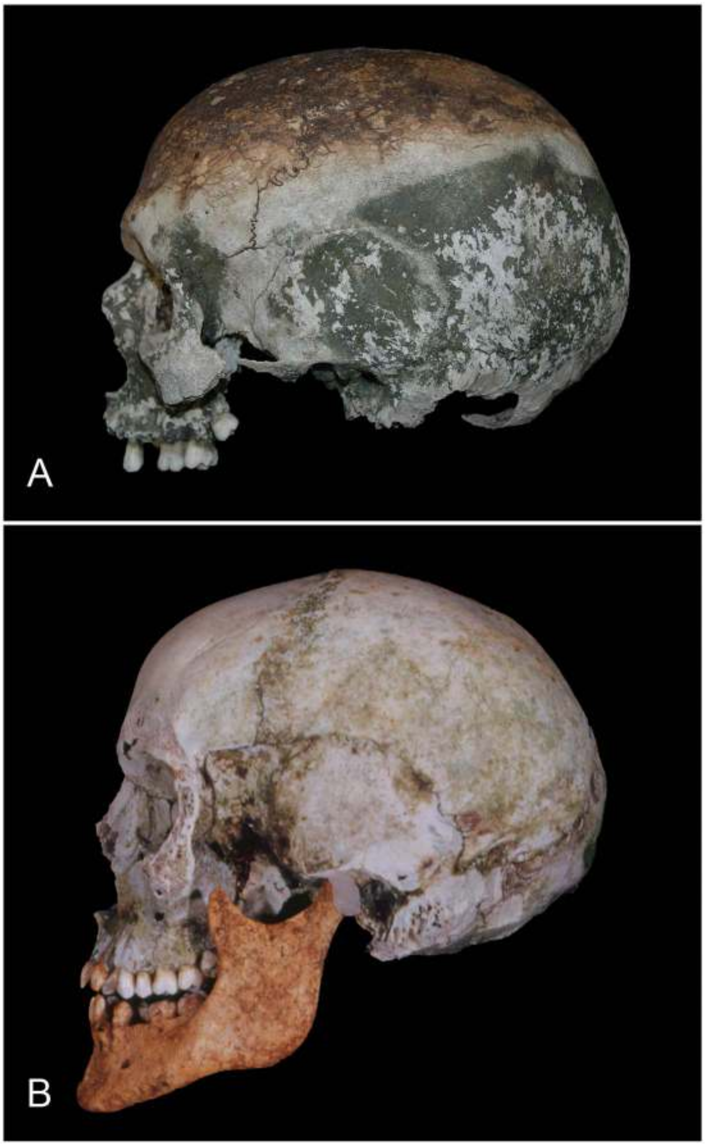

Figure 12.2 Differential staining: (a) sun-bleached cranium exhibiting a darker soil stain on the superior aspect due to contact with an organic soil horizon, algae staining on the face and sides of the cranial vault; and (b) sun-bleached skull with minimal algae staining on the vault and face and prominent soil staining of the mandible and dentition.

bleaching, bones may show substantial surface cracking and exfoliation (e.g., Behrensmeyer 1978) due to exposure to additional environmental conditions such as cold, heat, moisture, and wind (Figure 12.3a) (Chapter 11). Further, bones may be differentially bleached depending on their position relative to the ground surface. For example, Figure 12.3b exhibits a skull from a forensic context in which the left side of the mandible remained in contact with the soil, while the cranium was resting on the surface with the left side exposed to the sun. Figure 12.3c exhibits a differentially stained sacrum from an archaeological context. In this case, the sacrum remained partially buried with only the superior aspect exposed to the sun.

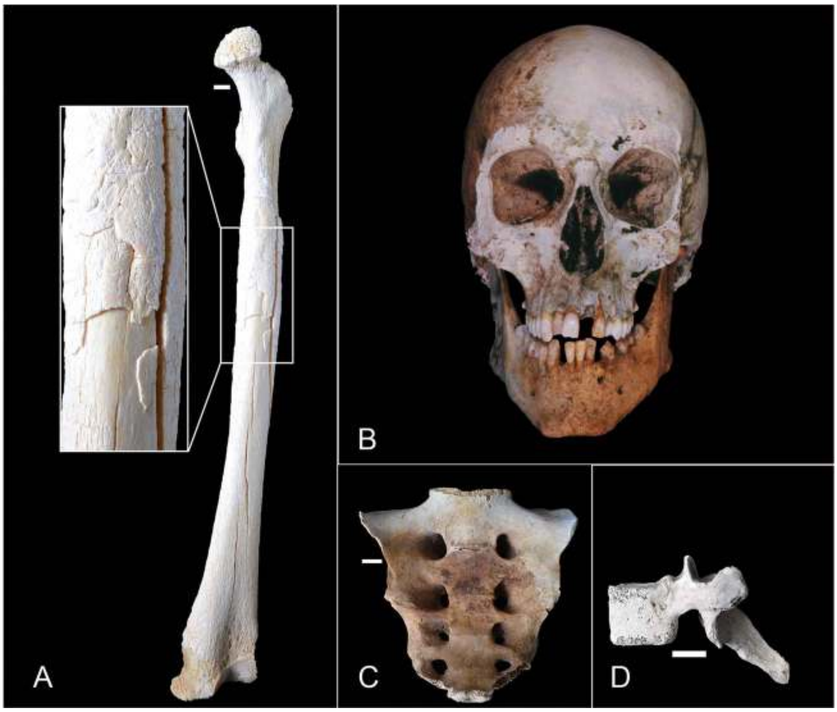

Figure 12.3 White coloration due to sun bleaching and fire exposure: (a) archaeological left femur displaying sun bleaching with surface cracking and exfoliation; (b) skull with sun bleaching on face and cranial vault; (c) archaeological sacrum showing sun bleaching of superior aspect; and (d) calcined thoracic vertebra.

It is important to note that bones also may appear white due to other circumstances. For example, exposure to intense heat or fire also may change bones to a variant of the color white (calcined). Much like UV radiation, intense heat can destroy organic materials in and associated with bone, therefore leaving only the inorganic component (Chapter 14). Figure 12.3d displays a vertebra exposed to fire and the associated white color which could be easily mistaken for sun bleaching. Bone also may have a white appearance due to the presence of adipocere, the remnants of the lipid hydrolysis during decomposition (Aufderheide 2011; Ubelaker and Zarenko 2011; Chapter 5). While process bleaching and fire alter the entire constitution of the bone, adipocere is normally adhered only to the internal and external surfaces of the bone and has a waxy, greasy texture that turns friable when dried. For example, Figure 12.4 exhibits examples of adipocere associated with bones from forensic contexts. Figure 12.4a displays adipocere on the proximal end of a right ulna, while Figure 12.4b displays adipocere on the internal surface of the medullary cavity of a femoral diaphysis. Adipocere also can be noted on the inferior surface and external auditory meatus of the cranium in Figure 12.1a.

Other Chemical Staining

During the process of preparing skeletal remains from forensic contexts for examination or for commercial preparation (e.g., teaching specimens), chemical agents may be used

Figure 12.4 Adipocere: (a) proximal right ulna with minimal adipocere development (white areas); and (b) femoral shaft exhibiting adipocere in the medullary cavity.

for the purposes of degreasing and/or whitening bones (Figure 12.5). Depending on the amount of soft tissue and lipids remaining, different chemicals may be used to treat skeletal remains. As more organic components are removed, the bone will become increasingly white; however, it is very difficult to remove all of the organic material associated with or in bone without altering the chemical composition, surface, or shape of the bone (Figure 12.5a). In the preparation of skeletal materials for forensic examination, once an acceptable level of soft tissue and lipids are removed with the use of a degreasing agent, processing should cease (Mairs et al. 2004). This is imperative for the preservation of evidence and molecular structures such as DNA (Fenton et al. 2003; Steadman et al. 2006). A mixture of detergent, sodium carbonate, heated water, and microwaving have been determined to be the most efficient methods of processing that also yielded the most total DNA (Lee et al. 2010; Steadman et al. 2006). Processing, however, will degrade the proteins of soft tissues and lipids, and caution must be taken so that over-processing does not affect the structural integrity of the bone (Figure 12.5a). After this preparation process the bone may still have a yellowish hue due to the retention of some lipids.

If the skeletal remains are commercially prepared for sale as teaching materials, the next step after lipid removal will be to treat the bones with a bleaching agent such as sodium hypochlorite (NaClO) or hydrogen peroxide (H_2O_2) (Rennick et al. 2005). A bleaching agent is a chemical which can whiten or decolorize substances containing *chromophores*—groups of atoms which absorb visible light and reflect or transmit the light that is not absorbed, as color. Bleaching agents destroy chromophores through oxidation or reduction, resulting in the removal of color (Joiner 2006). Unfortunately, many bleaching agents also attack and destroy the organic and mineral component of bone, so this step is not advised for treating materials from forensic contexts (Rennick et al. 2005; Steadman et al. 2006). Skeletal materials are usually a bright white color after the bleaching process (Figure 12.5c and d).

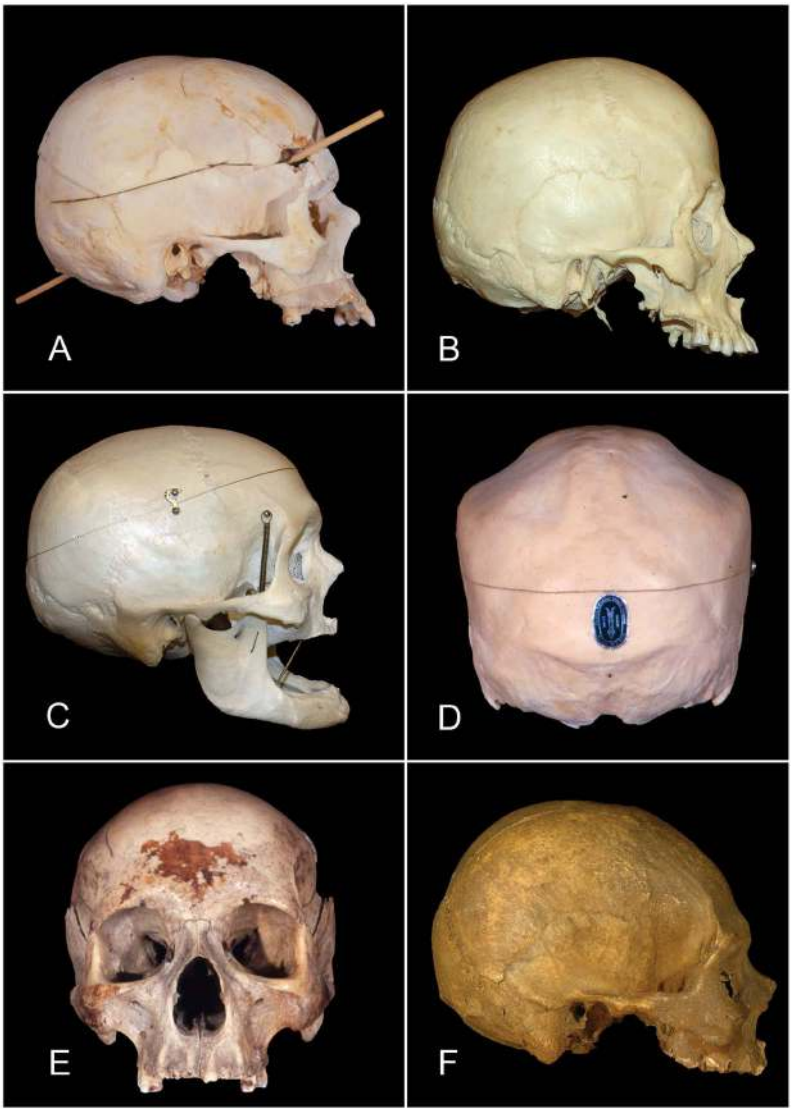

Figure 12.5 Chemically treated crania exhibiting differential coloration: (a) forensic skull displaying white coloration due to over-processing; (b) commercially prepared teaching cranium from China, bleached off-white; (c) commercially prepared teaching skull most likely from India, bleached white; (d) commercially prepared teaching cranium most likely from India, bleached white; (e) bleached white teaching cranium most likely from India that is slightly dirty with a patina and dark colored, adhered packing material is present on the frontal and right zygomatic; and (f) commercially prepared teaching cranium that is dirty with a patina from handling.

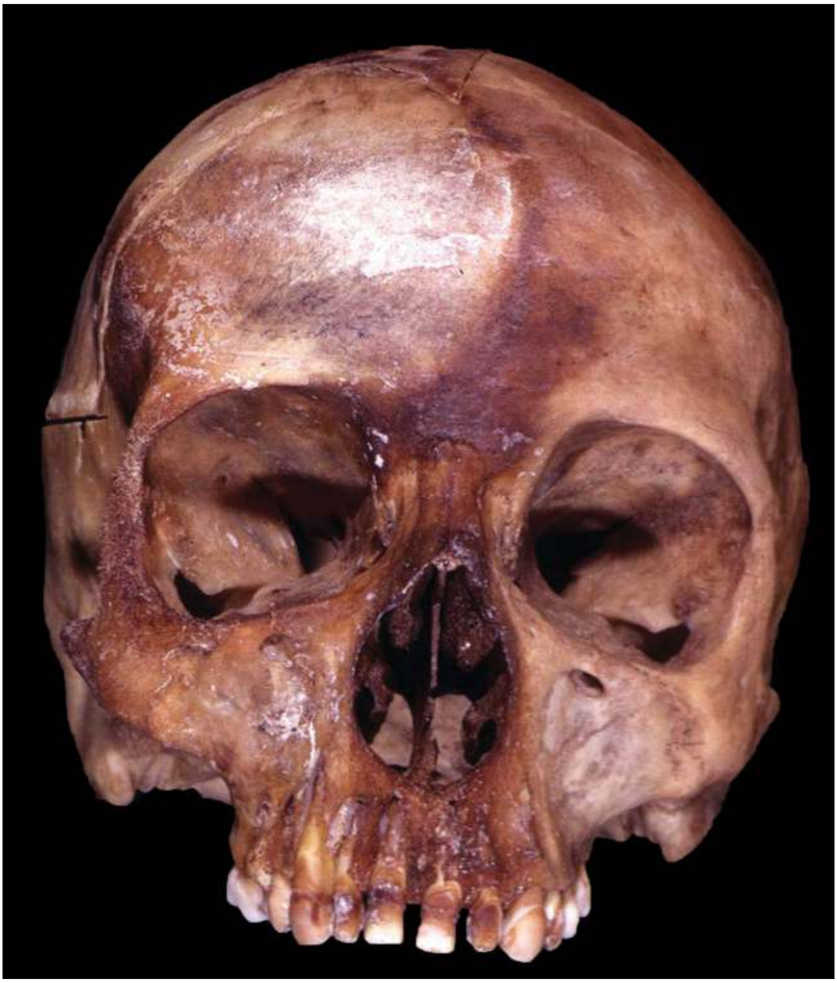

Figure 12.6 Cranium from forensic context exhibiting chemical staining produced by hydrochloric acid that was used to dissolve identifying feature of the decedent.

Several authors have discussed how assailants have used corrosive chemicals to dispose of or mutilate a body (e.g., Maples and Browning 1994; Ubelaker and Sperber 1988). At present there are very few publications that reference the clandestine use of corrosive chemicals on human remains, and research in this area only briefly mentions associated color changes (e.g., Cope and Dupras 2009; Hartnett et al. 2011). Areas of dark brown staining have been noted on remains which have been exposed to hydrochloric acid (HCl) (Figure 12.6), while suspected exposure to sodium hydroxide (NaOH) is thought to whiten bone (Christensen and Meyers 2011; Cope and Dupras 2009).

Staining—Skeletal Teaching Materials

Most materials in skeletal teaching collections, particularly those in North America, were likely procured from India or China (Chapter 8). Due to variation in commercial preparation techniques, the color of this material may vary (Schultz 2012). Figure 12.5 compares several examples of skeletal material legally purchased from clearing houses for the purposes of teaching. Figure 12.5b displays a cranium that originated in China, and it is common that the color of these materials varies from white to yellowish-white. Figure 12.5c–e compares materials that were prepared in India, and these materials are usually a bright white color, although they may show dark staining on the alveolar region due to the individual chewing betel nut while alive (Schultz 2012). Figure 12.5e is also interesting in that the cranium has paper (appearing as dark areas) adhered to the frontal and right zygomatic due to long-term storage. It is also important to note that after significant handling in the classroom setting, teaching material that was once bright white may appear dirty with a *patina*. The patina will consist of residual skin oils and dust or other particles and can appear as a dark brown or gray color with variable glossiness (Figure 12.5f). Maceration bleaching on professionally prepared skulls also includes in some cases an orange staining of unknown origin (Figure 12.7). Possible causes include incomplete bleaching of areas that were previously stained by decomposition or some kind of reaction with bleaching chemicals. These color changes likely will be accompanied by other, physical alterations to remains professionally prepared for teaching, including sectioning and mounting (Chapter 8).

Figure 12.7 Former anatomical teaching cranium exhibiting maceration bleaching with prominent orange staining, particularly to the frontal, of an unknown origin. (Image courtesy of James T. Pokines.)

Soil Staining

It is very common to observe staining on bones from outdoor contexts resulting from burial of the remains, or bone surfaces that are in contact with the soil surface (e.g., Figure 12.2a and b; Figure 12.3b and c). The coloration of the staining is related to the soil composition, which can include various minerals and organic matter. Color is the most obvious characteristic of soil that we first notice, which is the result of either the soil particles or the coatings of the soil particles (Schaetzl and Anderson 2005). For example, white soil coloration can be due to sodium salts, carbonates, and silt-sized or smaller quartz grains without pigmentation coatings. Dark soils with a black or brown coloration are the result of organic matter (humus) as well as magnetite (Fe_3O_4). Black or bluish-black colorations are the result of reduced manganese (Mn^2+). Bright red and brown colorations are associated with well-drained soils and oxidizing conditions (iron-bearing).

In forensic contexts, soil staining on bone may be represented by various colors. The organic horizons of a mineral soil profile begin at the ground surface and are formed from the residues of decaying plant and animal remains (Brady and Weil 2002). A black or darker brown coloration on bones in contact with the ground surface is associated with the darkly colored organic matter that comprises the organic horizons (Chapter 5). It should be noted that teeth also may be stained differentially by soil contact. It is common for the anterior (single-rooted) teeth to be soil-stained, since they may be in contact with or become buried under the ground surface after detaching from the alveolus during decomposition (Figure 12.8).

Figure 12.8 Sun-bleached cranium exhibiting differential staining of teeth. After decomposition the incisors detached from the alveolus and were stained by contact with the soil.

Figure 12.9 Iron staining: (a) large mass of iron corrosion products adhered to a femoral diaphysis (Image courtesy of Rimantas Jankauskus); and (b) prominent orange area of iron staining with adhered rust on a long bone diaphysis. The light brown color is most likely due to exposure to sandy soil matrix.

It is common for buried skeletal remains from forensic contexts to exhibit brown discoloration. At the same time, buried skeletal remains from historical contexts have been described as displaying a uniform medium-to-rich chocolate brown coloration, resulting from a combination of tannins in the soil solution (soil water and dissolved load) and iron oxides in the soil (Schultz et al. 2003; Chapter 5). The interaction of bone within an environment is dominated by water, which transports ions, molecules, and particles in and out of bone (Millard 1996). Further, the chemical interaction between buried objects and the burial medium is mainly the result of the chemical nature of the soil solution (Pollard 1996), as the chemistry, pH, and Eh of the soil solution will control the diagenetic change to bone (Millard 1996). Therefore, in the burial environment bone staining will occur due to contact with the soil and through the interaction with the soil solution. While darker-colored minerals and organic matter present in the soil solution will result in darker staining such as dark brown, buried bone exhibiting a lighter-colored staining such as tan (e.g., Figure 12.9b) may be buried in a lighter colored mineral soil low in organic matter and comprised of smaller quartz grains with lighter colored pigmentation coatings.

Dark staining of buried bone due to manganese (IV) oxides/hydroxides also has been reported in archaeological contexts. Manganese, present in many minerals, is one of the most abundant metals in soil (Emsley 2001). Depending on its state, manganese can form compounds with different colors, and these compounds may stain bone different colors. For example, manganese dioxide (MnO_2) can stain bone a black color (Cukrowska et al. 2005; Shahack-Gross et al. 1997), manganese (II) carbonate ($MnCO_3$) can stain bones a pink to red or brown color (Anthony et al. 2010), and permanganate ions ($KMnO_4$) can stain bone a purple color (House 2008). Interestingly, using various laboratory procedures, Cole and Waldron (2016) identified a purple stain associated with medieval archaeological skeletons. The purple coloration was correlated with the presence of high levels of the purple acid phosphate (PAP) enzyme and trace amounts of copper, iron, manganese, and zinc. It was suggested that the purple coloration was consistent with a plant or fungal origin due to the combination of PAP and the specific trace elements (Cole and Waldron 2016). While specific colors of bone staining from archaeological contexts may be due to different taphonomic agents, it is important to note that buried archaeological remains undergo a complex taphonomic environment. Therefore, various laboratory tests may be required to determine the exact mineral composition of bone staining when multiple taphonomic agents have been at work.

Metal Staining from Artifacts

Goffer (2007) defined corrosion as a natural destructive environmental process resulting in decay or waste of most metals and alloys. Apart from noble metals such as gold and platinum, the natural corrosion tendency of metals and alloys occurs when combined with an oxidizing substance (e.g., oxygen, fluoride, etc.). This corrosion process is a reversal of the metallurgical process back to the natural, chemically combined form found in the crust of the Earth. For example, rust noted on the surface of exposed iron and steel has the same chemical composition as natural iron ore (Goffer 2007). Corrosion of metal in contact with bone results in metal staining and possibly adhered corrosion products to the bone. In a forensic context, common metals that stain bone are iron (Schultz 2012; Schultz et al. 2003) and copper (Buikstra and Ubelaker 1994; Schultz 2012; Schultz et al. 2003), with mercury staining less commonly reported (Ubelaker 1996).

According to Janaway (2008), corrosion of metal in a burial environment is influenced by several variables that include the PMI, the chemical nature of the burial environment, and the composition and structure of the metal artifact. If the burial environment contains high levels of moisture, metals will corrode much faster, and corrosion products such as oxides, carbonates, and sulfates are produced when metals react with environmental chemicals such as oxygen, carbon dioxide, and salts (Cronyn 1990). In forensic contexts, the burial environment will contain moisture related to the decomposition process and percolating rainwater, and it may include a shallow water table. Further, Edwards (1996) and Banwart (1996) assert that it is the combination of pH and redox (an increase in oxidation or the loss of electrons) that will influence metal corrosion in the burial environment. For example, metal will not corrode in a burial environment with low redox (decrease in oxidation or a gain in electrons) values, while metals with high redox values will be more susceptible to corrosion (Janaway 2008). At the same time, while an alkaline (higher pH) burial environment will tend to stabilize the corrosion matrix in most metals, acidic (lower pH) conditions will corrode metals (Janaway 2008).

Janaway (2008) further emphasized how the chemical nature of the buried object will influence corrosion, by dividing metals into three groups based on their susceptibility to corrosion. The first group of metals is classified as corrosion-resistant, and common examples include gold or surgical steel used for body piercings and titanium alloys used for implants. The second group of metals is susceptible to an initial rapid corrosion phase, followed by the creation of a layer of stable corrosion products (e.g., copper). In addition, these metals can have an extensive metallic core preserved hundreds of years after burial. The third group of metals corrodes rapidly and does not form a layer of protective corrosion products. Iron would be an example of a rapidly corroding metal that can be characterized as completely lost over an extended PMI, or it can remain as a large mass of corrosion that may cover a reduced metallic core (Figure 12.9a).

Iron

Rust, a brown, crumbly corrosion product composed of hydrated iron oxide, is formed when iron and its alloys are exposed to a moist, oxygenated environment (Cronyn 1990; Goffer 2007). As corrosion proceeds into the metal, a thick overlying concretion of corrosion products can be formed over the iron artifact (Figure 12.9a) (Cronyn 1990). Eventually, the metal can be completely corroded and only represented by a void within the overlying concretion. According to Cronyn (1990), in moist and oxygenated environments, the oxidized iron can produce an area of corrosion products that can be considerably larger than the dissolved metal (Figure 12.9b). Hence, staining of bone can occur when the item is in direct contact with the corroding iron object or in proximity to the corrosion products in the soil. Iron staining of bone also may be used to recognize out-of-context cemetery remains, as iron artifacts associated with the coffin such as nails (Chapter 5) can stain bone an orange color, and adhered corrosion products may be present (Schultz 2012; Schultz et al. 2003).

Corrosion of iron results in a layer/crust of corrosion products that can display a variety of colors (Cronyn 1990). Iron excavated from damp, aerated sites is commonly recovered as a mass with a red/brown coloration composed of iron oxides and carbonates. The corrosion products consist of iron (III) oxyhydroxides (FeO·OH), with the main component in the form of red/brown/yellow goethite (αFeO·OH), including orange lepidocrocite (γFeO·OH). A black coloration to the corrosion products of iron can occur from several different compounds. When iron objects are subjected to a wet, anaerobic burial environment because of iron (II) sulfide (FeS) formed by sulfate-reducing bacteria, a black layer can be formed. Also, a black coloration due to the formation of black oxide magnetite (Fe_3O_4) can form at marine sites with low oxygen (Chapter 7). Interestingly, Cronyn (1990) further mentioned that green-colored rust is also possible as a mixture of iron (II) and iron (III) hydrated oxides. While it is observed occasionally on marine cast and wrought iron, it also has been observed on wrought iron from land sites. Considering that the green coloration from copper and copper alloys found on bone is most often a stain and not an adhered green corrosion product, this rare example more than likely does not have to be considered when interpreting green staining as copper derived.

Lastly, a bright blue to blue-black coloration is much rarer and can be displayed on bone resulting from deposits of vivianite (iron phosphate). In the form of iron (II) phosphate ($Fe_3(PO_4)_2{\cdot}8H_2O$), vivianite exhibits a whitish-gray coloration in its unoxidized condition when first excavated, but when exposed to air the mineral changes color to a brilliant blue (Cronyn 1990; Guthrie 1990; McGowan and Prangnell 2006). When referring to archaeological settings, this mineral staining of buried organic remains can occur when iron phosphate and water are present in conjunction with low levels of oxygen and sulfide (McGowan and Prangnell 2006). With the combination of a phosphate and iron source, there must be a reducing and acidic environment for vivianite to form (Courty et al. 1989). Examples of a reducing environment include acid groundwater, deep water, waterlogged soil, and other anaerobic conditions (Courty et al. 1989; Johanson 1976; Mann et al. 1998; Martill 1991; Thali et al. 2011). While vivianite staining traditionally has been reported in the paleontological literature (Guthrie 1990; Martill 1991), this staining also has been sampled on skeletal remains from US servicemen listed as missing in action from the Vietnam War, which indicates that this staining can be produced on bone during much shorter PMIs than previously believed (Holland et al. 1997; Mann et al. 1998). According to Mann et al. (1998) based on experience and summarizing the literature, the iron source for the formation of vivianite on bone can also come from a nearby piece of iron, a common occurrence on battlefield and air crash sites, in addition to the soil.

Copper and Copper Alloys

Copper and copper alloy staining is recognizable on bone as a green to greenish-blue coloration (Buikstra and Ubelaker 1994; Schultz 2012; Schultz et al. 2003). Copper staining has been reported in the forensic literature as one of the taphonomic clues to recognize out-of-context cemetery remains as artifacts comprised of copper, including coffin hardware or jewelry, can corrode and stain bone a greenish coloration (Figure 12.10) (Schultz 2012; Schultz et al. 2003). In forensic contexts copper staining may be present on bone because

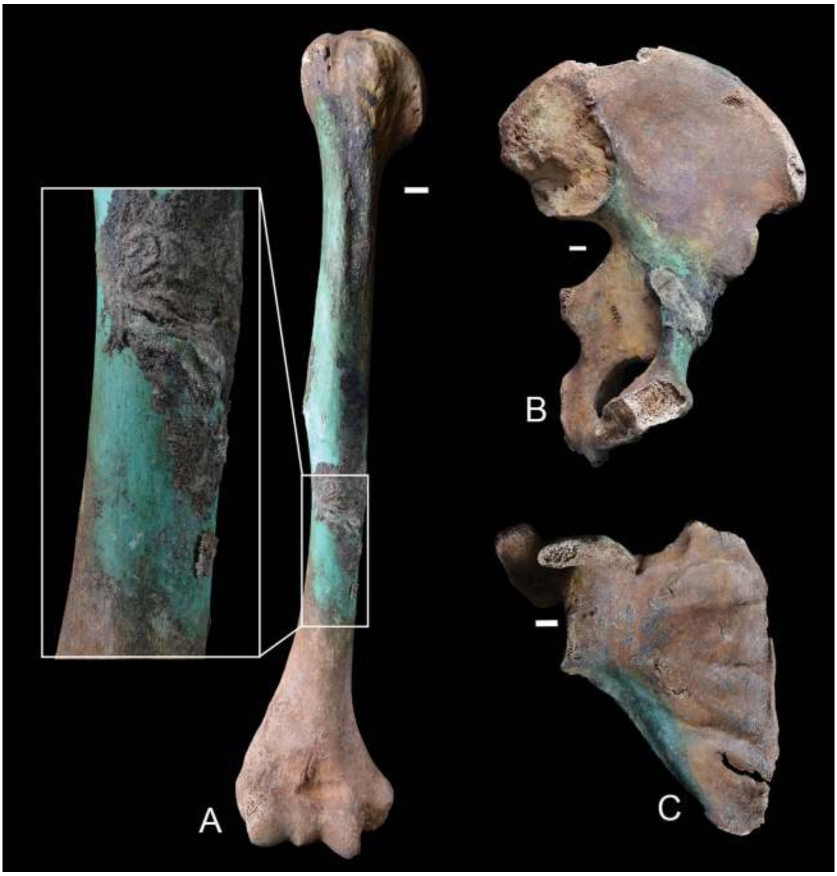

Figure 12.10 Copper staining exhibited on remains from an historical context: (a) copper staining and fabric preservation on the diaphysis of a right humerus; (b) copper staining and fabric preservation on the superior pubic ramus and ilium of a left os coxa; and (c) copper staining along the anterior axial border of a right scapula.

Figure 12.11 Copper staining exhibited on remains from forensic contexts: (a) prominent staining of the superior pubic area (arrow) most likely from clothing fasteners; decomposition staining is notable on the iliac blade; and (b) faint staining on the spinous process of a thoracic vertebra from a copper bullet jacket (arrow).

of copper alloy-based clothing artifacts such as buttons and zippers and from the copper jacket of a bullet (Figure 12.11).

The two most common alloys of copper are bronze and brass. Brass, which is stronger and harder than copper, is primarily a mixture of copper and zinc, while bronze, which is harder and has a higher tensile strength than copper, is primarily a mixture of copper and tin (Goffer 2007). While copper and copper alloys are generally resistant to corrosion under normal atmospheric conditions, these metals will tarnish by contact with pollutants such as hydrogen sulfide and/or carbon dioxide (Goffer 2007). Eventually, corrosion will produce a green surface layer (also) referred to as a *patina* with the metallic core remaining unchanged. Compounds such as copper carbonates, oxides, and chlorides comprise the copper patina, while the patina for bronze and brass also includes oxides of tin and lead (Goffer 2007). Slow, controlled corrosion to the surface of copper and copper alloys is due to moisture, carbon dioxide, oxygen, air pollutants, and sea water (Cronyn 1990; Goffer 2007). In addition, buried copper objects may become severely corroded as they react with soil pollutants and components of the soil (Goffer 2007).

According to Cronyn (1990), there also can be color variation of the corrosion products resulting from the environment and type of copper alloy. For example, the common green coloration observed on bone is the result of emerald/dark-green malachite, basic copper (II) carbonate ($CuCO_3 \cdot Cu(OH)_2$). The hue of the green can be darkened by the addition of sulfides of copper and lead or lightened by the addition of lead carbonate and other compounds. A blue color can also develop from another basic copper (II) carbonate, azurite ($2CuCO_3 \cdot Cu(OH)_2$), while yellow-green patinas can form on copper alloys exposed to the atmosphere from basic copper (II) sulfate, brochantite ($CuCO_4 \cdot 3Cu(OH)_2$). Further, corrosion of copper artifacts can also produce a crust of corrosion products that usually contain the same minerals as the patinas (Cronyn 1990).

On occasion, the presence of copper will aid in the preservation of organic materials (McIntosh 1999). If cotton clothing is present, the copper may act as a preserving agent, and it is not uncommon to see small pieces of cloth adhered to areas that are stained green. For example, both the historic period humerus and os coxa in Figure 12.10a and b exhibit preservation of cotton material adhered to the stained areas.

Mercury

Mercury staining from dental amalgam restorations is one of the less commonly reported chemical stains. A dental amalgam is classified as a solid emulsion metal mixture comprised of approximately 50% metallic mercury (Hg^0) by mass (Richardson et al. 2011). While the formulations will vary in the mercury content from 43% to 50.5% by mass, the powder mixture typically will contain a variety of metals such as silver (40%–70%), copper (12%–30%), tin (12%–30%), indium (0%–4%), zinc (0%–1%), and palladium (0.5%) (Berry et al. 1994). Although it is now accepted that there is a continual release, and therefore exposure of Hg^0 in living persons with amalgam fillings (USFDA 2009), it is not common to see mercury staining of the dental anatomy.

Staining of osseous materials by mercury is the result of postmortem deterioration of the amalgam fillings. In the only case study describing the taphonomic agent of mercury stains to the dental anatomy, Ubelaker (1996) described a metallic black stain to the oral cavity of an exhumed cemetery skeleton with a significant number of dental amalgam restorations. Staining was present on the anterior dentition of both the maxillary and mandibular teeth, as well as the mandible. In addition, it was reported that the dental amalgam restorations were deteriorated. While the taphonomic agent for the deterioration of the amalgam fillings and resultant staining of the osseous surfaces was not known, Ubelaker (1996) suggested that the staining may have been produced from the presence of sulfuric acid (H_2SO_4) in the burial environment. For example, sulfur dioxide (SO_2) could have been released from decomposition, producing sulfuric acid in the humid environment of the vault. The interaction of the sulfuric acid, or possibly some other compound, released the mercury from the amalgam restorations, producing the staining. Figure 12.12a through c displays an example of the deterioration of amalgam fillings of the mandible in a forensic case. In this example, there is a grayish stain on the enamel of the teeth that contain amalgam fillings, and the concomitant bone surfaces of the mandible are also stained. Of note is the prominent stain on the lingual surface of the mandible. It is important to note that this stain was only located on the mandible and may be the result of a unique compound in the postmortem environment reacting with the amalgam fillings.

Organic Staining

Bones from outdoor contexts typically will interact with plant and tree materials, resulting in organic stains on the bone. According to Bass (1997), bones in shady areas may exhibit moss or green algae growth (Chapter 11) during the first year of exposure. Green staining from moss and algae is the result of pigments such as chlorophyll (greens), xanthophyll (yellows), and carotenoids (oranges and reds) (Davies 2004) invading and binding tightly with the bone surface. Other examples of organic staining present on bones can be due to the interaction of bone with various staining agents such as leaves, acorns, wood, roots, or the decomposition of pine needles (Chapter 5).

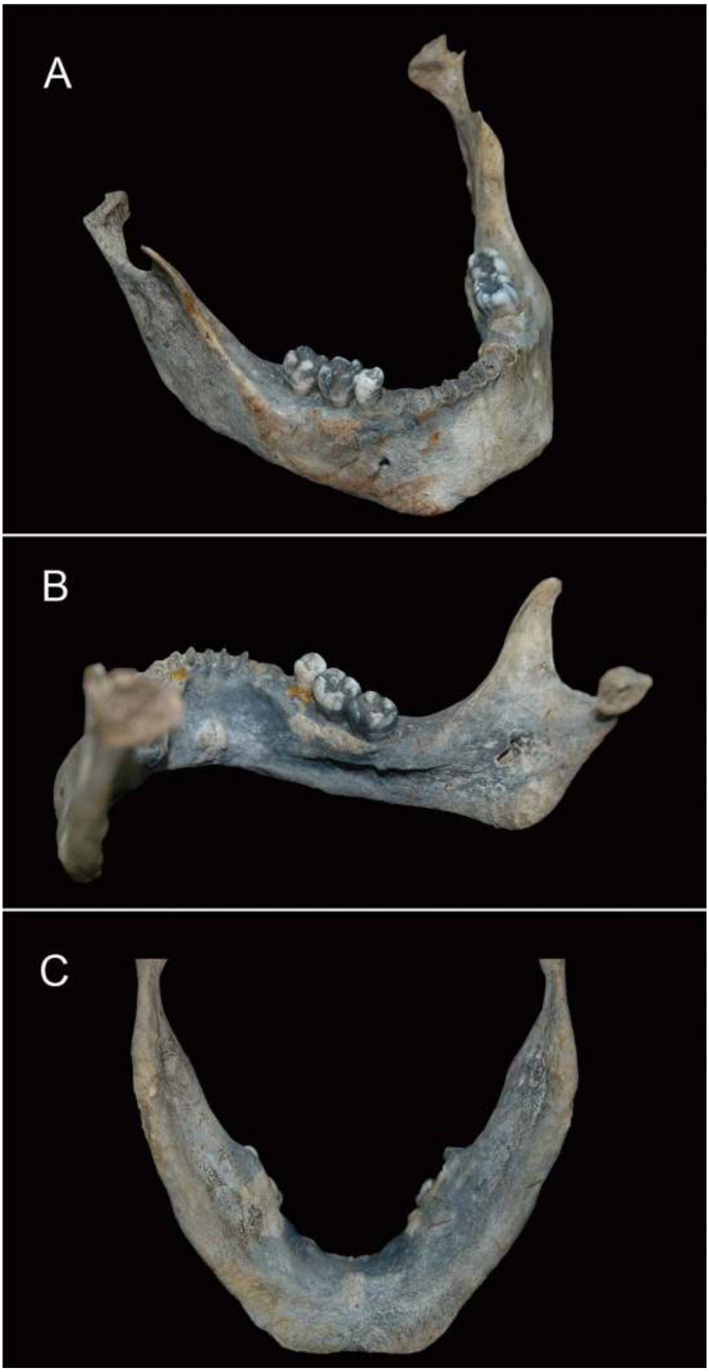

Figure 12.12 Mandible with amalgam mercury staining: (a) anterior view exhibiting staining on buccal side of enamel; (b) posterior view with staining on the lingual surfaces of enamel and alveolus; and (c) inferior view with extensive bone staining.

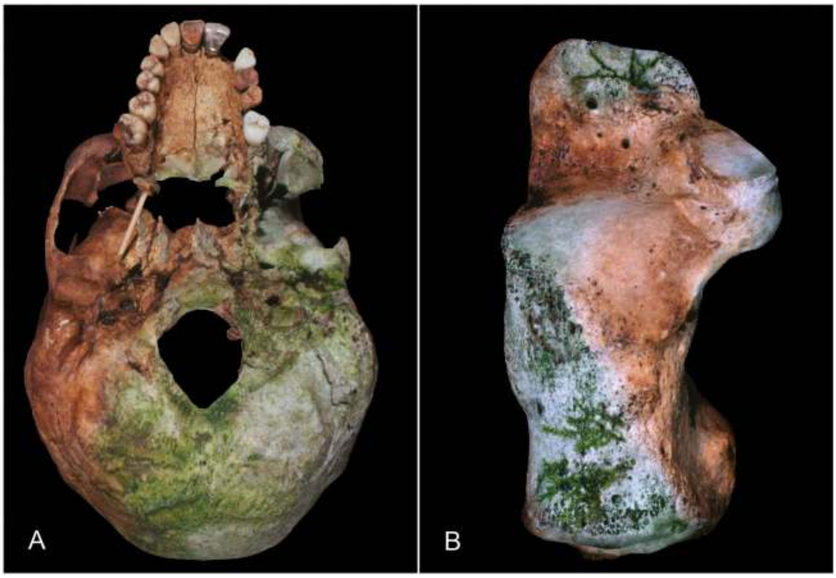

Figure 12.13 Organic staining: (a) inferior view of cranium exhibiting algae staining; and (b) sun-bleached left calcaneus with moss and soil staining. Note that the moss growth corresponds with the exposed (sun-bleached) areas.

Algae

While algae growth on human remains in aquatic environments has been associated with the determination of the postmortem submersion interval (PMSI) (Casamatta and Verb 2000; Haefner et al. 2004; Zimmerman and Wallace 2008; Chapter 7), green staining from algae is also commonly found on terrestrial bones in moist shaded areas (Bass 1997; Janjua and Rogers 2008; Pokines 2016; Ubelaker 1997). Algae are nonvascular plants without true roots, stems, or leaves that typically possess chlorophyll and are photosynthetic (Hall 2012). Forensically, algae can be important botanical evidence used to link a suspect to a specific aquatic scene, as well as placing a suspect at a scene during a specific time of year (Hall 2012; Hardy and Wallace 2012; Siver et al. 1994). While it is common to note green algae growth on submerged remains, it is also common to observe green organic staining from algae growing on bone in terrestrial environments (Figure 12.13a), and this would indicate that the bones had been in a moist, shady environment.

Mosses

Mosses are nonvascular and flowerless plants of the class Musci that can grow on bone and produce green staining (Bass 1997). Mosses grow in moist and shady areas (Coyle 2004) and are usually the first plants to colonize newly exposed bare rocks, ground, and other abiotic surfaces (Hallingbäck and Hodgetts 2000). While mosses may appear to have stems, roots, and leaves, they are a small green organism lacking these structures (Hall 2012). Although they have no true roots, they contain root-like structures that allow them to cling to various surfaces (Hallingbäck and Hodgetts 2000). Also, while they are usually small organisms, mosses can grow as large mats across the ground and are on average only a few centimeters in height from their surface of attachment (Coyle 2004). Forensically, adhered moss growth on bone can also be useful in contributing to the information used to generate a PMI (Cardoso et al. 2010; Hall 2012). Green organic staining also may occur from mosses adhered to and growing on bone (Figure 12.13b).

Root Staining and Etching

Root etching is a common taphonomic modification that is recognized on the bone surface as a dendritic pattern of shallow grooves or tracts (Behrensmeyer 1978; Buikstra and Ubelaker 1994; Schultz 2012; Schultz et al. 2003; White and Folkens 1991; Chapter 5). According to Behrensmeyer (1978:154), the pattern results from "dissolution by acids associated with the growth and decay of roots or fungus in direct contact with the bones surfaces". Discoloration of the tracts may also occur through acid decalcification of the bone (Buikstra and Ubelaker 1994). Root etching is more commonly observed on archaeological material, and it is less common to observe this taphonomic modification on forensic remains due to shorter PMIs (Schultz 2012; Schultz et al. 2003). It is possible, however, to observe dendritic patterns of darker staining from plant roots on the bone surface of forensic remains (Figure 12.14a).

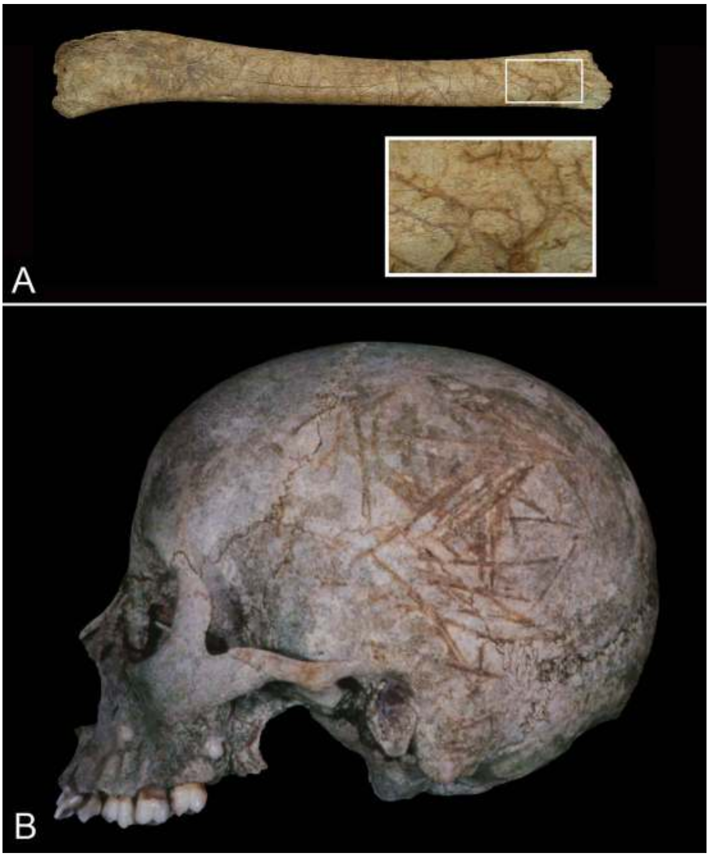

Figure 12.14 Organic staining: (a) juvenile white-tailed deer (*Odocoileus virginianus*) tibia showing dendritic pattern of root staining; and (b) sun-bleached cranium with minimal algae staining and pine needle etching of the cranial vault with accompanying tan-colored staining.

Decomposing Plant Material Staining

Another example of organic staining found on bones can be the result of decomposing plant materials, including acorns, leaves, wood, and pine needles that come in direct contact with skeletal material (see Chapter 5 for discussion of tannins as they relate to coffin burials). It may be possible to discern specific types of organic material based on the bone coloration and staining patterns. For example, bones in contact with acorns can display circular patches of darker staining, ranging from a brown to dark grayish-brown coloration (Pollock et al. 2018). While maple leaves exhibit larger areas of staining than acorns, the staining coloration is lighter in color than acorns and darker than staining from oak leaves (Pollock et al. 2018). Pine needle staining can be present as a tannish coloration (Figure 12.14b), and this taphonomic change can be observed as an unorganized pattern of linear staining (Dupras et al. 2011). There may also be superficial etching of bone because the decomposing pine needles are acidic and react with the base ions of the bone surface.

Mineral Precipitates and Other Encrustations

On some occasions bone surfaces may be altered by either mineral precipitates or other mineral encrustations and thus alter the color of bones. For example, in both marine and mineral-laden burial environments, sodium chloride (NaCl or "salt") may be dissolved in solution. This solution may penetrate the bone, and as the water evaporates the salt will begin to crystallize (Chapter 7). The crystals may expand and cause damage to the bone, or form crystals on the bone surface (Figure 12.15). Other minerals such as vivianite (see previous

Figure 12.15 Cranium exhibiting salt precipitates with close-up (inset).

discussion on iron) may form encrustations on the surface. In the marine environment bones may also show color and surface alterations due to barnacles. Although not a mineral, but an animal, barnacles may grow on bone, thereby altering the bone surface and affecting the color of the bone (see Chapter 7 for discussion of barnacles in marine environments).

Bones in marine or burial environments with groundwater also exhibit staining and encrustations associated with calcium carbonate ($CaCO_3$). Calcium carbonate commonly manifests as segregations in soil, and occurs in a variety of forms, sizes, and consistencies (Fitzpatrick 2008). In precipitate formed calcium carbonate may permeate the bone and exchange for minerals in the hydroxyapatite, or it may form layers on the bone surface where it will appear as a white or off-white encrustation (Figure 12.16a through c). This type of mineral concretion forms frequently where water pools and then evaporates. The

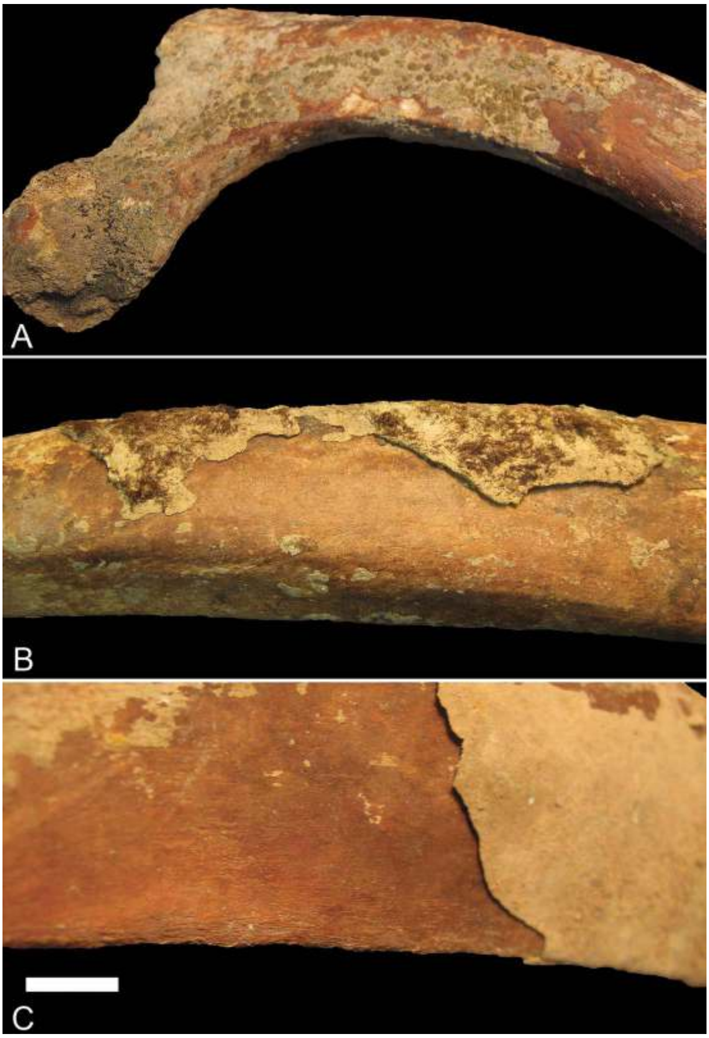

Figure 12.16 Calcium carbonate concretions from a freshwater environment: (a) cow (*Bos taurus*) rib showing calcium carbonate concretions with algae growth; (b) layer of calcium carbonate with algae growth; and (c) close-up showing layer of calcium carbonate on bone surface. Scale bar is 1 cm. (Images courtesy of Thomas Evans.)

encrustation may form as a distinct ring indicating the orientation of the bone while this process occurred. Later movement of skeletal elements may be detectable by the lack of horizontal alignment of the calcium carbonate ring (Chapter 20).

Miscellaneous Staining

It is common to note bone staining and color changes from a variety of other taphonomic agents that are associated with bones from modern forensic, ritual, and trophy contexts. For example, clothing can produce localized staining from the dyes used to color fabric, and it is sometimes possible to discern clothing remnants adhered to the bone from fabric comprised of natural plant-based textile fibers that have disintegrated. It also may be possible to discern the weave patterns of coarser fabrics on the surface of bones as a stain from the fabric dye. Figure 12.17 is an example of an os coxa exhibiting yellow staining on the medial surface. The decedent was wearing yellow short pants at

Figure 12.17 Yellow staining of the medial aspect of a right os coxa due to dye from yellow short pants that the decedent was wearing. Scale bar is 1 cm. (Image courtesy of James T. Pokines.)

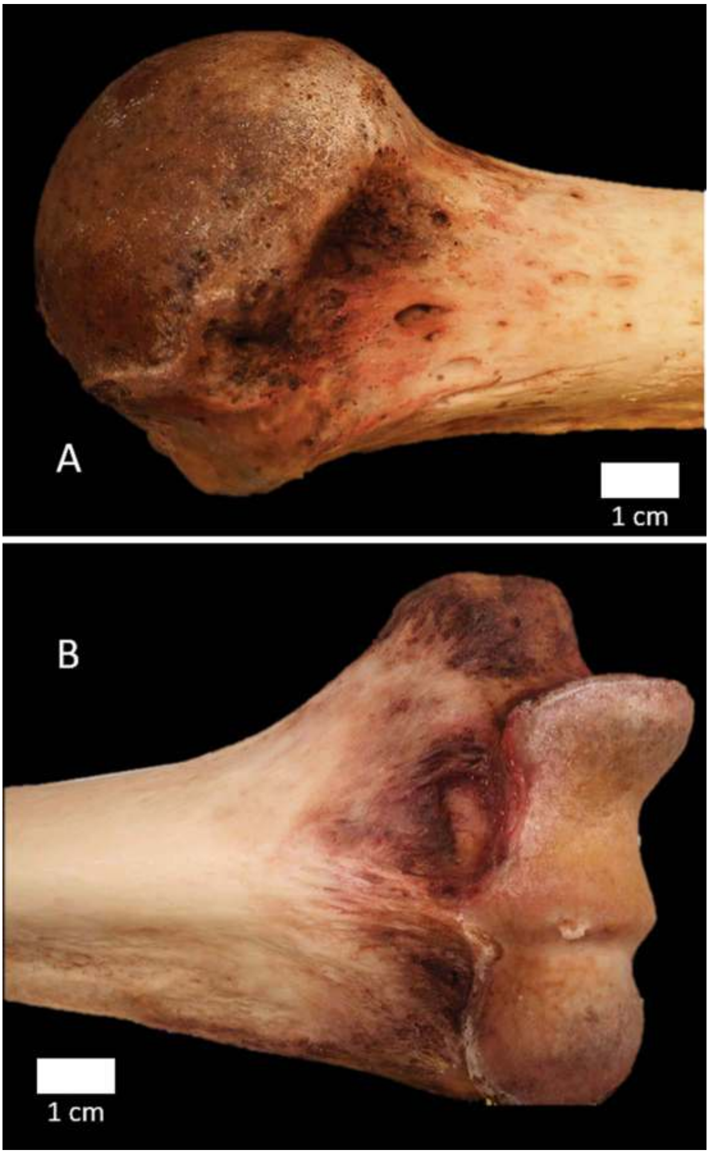

Figure 12.18 Pinkish stain on a proximal (a) and distal (b) right humerus from long-term storage of a skeleton that may have a bacterial/fungal origin. Scale bar is 1 cm. (Images courtesy of James T. Pokines.)

death, and the remains were received a year postmortem, with the bones of the pelvis stained yellow from the dye that was used to color the shorts. In addition, on occasion long-term storage of skeletal remains may result in staining and/or residues from mold, bacteria, insects, and from fats within bones that leach onto the cortical surfaces. Figure 12.18 represents a pinkish stain on a humerus from long-term storage of a skeleton that is associated with bacterial/fungal colonization; the staining remained after additional maceration removed the colonizing organisms.

Various patterns of taphonomic modifications are important when interpreting medicolegal significance of skeletal remains (e.g., Schultz 2012). Several authors have noted staining and various residues associated with collecting and displaying war trophies (Sledzik and Ousley 1991; Wiley and Leach 2009; Chapter 8), as well as associated with ritual use of skeletal remains from Palo contexts (Schultz et al. 2020; Wetli and Martinez 1981; Winburn et al. 2016). For example, common stains and residues noted on bone from a variety of Palo contexts include candle wax, chalk, ink, paint, animal blood, glue, localized metal staining, and carbonization from burning (Schultz et al. 2020; Wetli and Martinez 1981; Winburn et al. 2016; Chapter 8).

Other Considerations Regarding Taphonomic Bone Staining

Depositional Significance of Staining Patterns

While staining colorations and patterns can be important diagnostic clues when determining taphonomic agents, overall soil staining patterns can be important indicators when determining depositional context. For example, differential staining of bones that have been in contact with the ground surface is important in determining if skeletal remains had been moved prior to discovery by investigators (e.g., Pokines 2016; Schultz 2012; Chapter 20). If the soil-stained surface is facing up and not in contact with the ground surface, this would be a clear indication that the remains had been disturbed recently. In addition, staining patterns can indicate if remains originated from burial or surface depositions. Skeletons that exhibit sporadic color patterning most likely originated from surface depositions (Pollock et al. 2018), while bones with more uniform staining most likely originated from a burial origin that could be a forensic or historic/cemetery context (e.g., Pollock et al. 2018; Schultz 2012; Schultz et al. 2003; Chapter 5). It is important to note, however, that buried remains found out of context, or partially exposed, that are uniformly stained can exhibit both sun bleaching and organic staining on the exposed surfaces (Figure 12.3c).

The Association of Taphonomic Color Changes and Postmortem Interval

With the loss of soft tissues during advanced decomposition, exposed skeletal remains will undergo a progression of taphonomic modifications due to subaerial weathering that include sun bleaching, cracking, and exfoliation of the outer cortical layers (Behrensmeyer 1978; Cutler et al. 1999). Estimation of the PMI using weathering patterns for skeletonized remains can be influenced by various taphonomic and environmental variables (Bass 1997; Janjua and Rodgers 2008; Schultz et al. 2018; Chapter 11). There are limited studies, however, by forensic anthropologists that only provide general guidelines for PMI estimation based on the progression of weathering alterations to bones (e.g., Galloway 1997; Komar 1998). Since bone organic staining can be present soon after deposition and before weathering degradation, it is surprising that PMI guidelines have not been developed for human skeletal material using taphonomic staining, in conjunction with early weathering alterations.

Several recent studies using pig (*Sus scrofa*) bones have evaluated how quickly color changes to bone can occur (Huculak and Rogers 2009; Pollock et al 2018; Schultz et al. 2018). For example, color changes from organic staining (wood and plant matter) can manifest two months after bones are exposed (Pollock et al. 2018). In addition, sun bleaching in an open environment can also be exhibited as early as two months after deposition (Schultz et al. 2018). Since Schultz et al. (2018) have demonstrated that the weathering stages by

Behrensmeyer (1978) could be increased by forensic anthropologists to include early sun bleaching stages that occur before cracking is scored along the bone surface, it is important to note that the initiation of sun bleaching is contingent upon the density of the tree cover. Therefore, future studies should consider using a combination of sun bleaching, soil staining, and organic staining to develop PMI estimates of human remains prior to bone degradation.

Conclusions

In forensic cases involving the analysis of human skeletal remains, it may become vital to reconstruct and interpret associated taphonomic events (Chapter 20). Taphonomic criteria can be useful in determining information such as forensic context (e.g., Pokines 2016; Schultz 2012), body movement, identification of associated artifacts, and possible perimortem events. Bone staining and color changes may provide vital clues about the burial or depositional environment and about associated burial artifacts. Determining the cause of bone staining may be very helpful with the interpretation of taphonomic events, but it is imperative to recognize that different taphonomic agents can create similar coloration or staining on bone. For example, bones with a white color may have been sun bleached, burnt, have mineral or adipocere adhesions, or have been chemically altered. Green staining may be related to algae or moss growth, or oxidation of copper artifacts. Bones with brown coloration may have been in contact with soils, water, or may be dirty from handling. It is also possible, as shown in Figure 12.2, that bones may display multiple color changes related to different taphonomic events. See Table 12.1 for summary of taphonomic staining agents and associated color changes.

Table 12.1 Taphonomic Agents and Associated Bone Color Changes

Taphonomic Process	Possible Associated Color
Chemical Staining and Natural Bleaching	
Sun Bleaching	Bright white to gray
Commercial Preparation	Yellow to bright white
Industrial Chemicals	Brown, white (dependent on chemical)
Soil Staining	
Humic acids	Dark brown, black
Manganese dioxide	Black
Manganese carbonate	Pink, red, brown
Permanganate	Purple
Metal Staining	
Iron	Orange, red, brown, black
Vivianite	Bright blue to blue-black
Copper and Copper Alloys	Green to bluish-green
Mercury	Gray/silver to black
Organic Staining	
Algae	Green
Mosses	Green
Roots and Decomposing Plant Materials	Light brown to black
Mineral Precipitates	
Salts	White (opaque crystals)
Calcium carbonates	White to off-white

Information for table derived from literature cited throughout this chapter.

Much like differential diagnosis in paleopathology, all bone surfaces should be examined and documented for any noticeable staining or color changes. Once colors are documented, it is then possible to review taphonomic literature to identify possible staining agents through the process of elimination. Additional clues from the depositional context and/or associated artifacts also may be very useful to assist in interpretation. For example, a bright white skull with hardware such as springs to hold the mandible in place, and screws and hooks to keep the calotte secured to the cranium, would indicate teaching or anatomical material (e.g., Schultz 2012; Chapter 8), and the bright white coloration would be due to deliberate chemical alteration from preparation. The anatomical location of the staining also may help to determine the taphonomic agent. For example, gray staining on the alveolus and tooth enamel would most likely be caused by the mercury in amalgam fillings, and it would be very unlikely to note this type of staining on other parts of the skeleton. Forensic anthropologists should be aware of the most common types of bone staining and color alterations as part of their investigation and interpretation of taphonomic events.

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References

Anthony, J. W., R. A. Bideaux, K. W. Bladh, and M. C. Nichols (2010) *Handbook of Mineralogy*. Mineralogical Society of America, Chantilly, VA.

Aufderheide, A. C. (2011) Soft tissue taphonomy: A paleopathology perspective. *International Journal of Paleopathology* 1:75–80.

Banwart, S. A. (1996) Groundwater geochemistry in the burial environment. In *Preserving Archaeological Remains in situ* ed. by M. Corfield, P. Hinton, T. Nixon, and M. Pollard, pp. 66–72. Museum of London Archaeology Service, London.

Bass, W. M. (1997) Outdoor decomposition rates in Tennessee. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 181–186. CRC Press, Boca Raton, FL.

Beary, M. O. (2005) *Taphonomic Effects of UV Light on Bone Surface: An Experimental Approach*. M.A. Thesis, Mercyhurst College, Erie, PA.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Paleobiology* 4(2):150–162.

Berry, T. G., J. Nicholson, and K. Troendle (1994) Almost two centuries with amalgam: Where are we today? *Journal of the American Dental Association* 125:392–399.

Brady, N. C., and R. R. Weil (2002) *The Nature and Properties of Soils* (13th ed.). Prentice Hall, Upper Saddle River, NJ.

Buikstra, J. E., and D. H. Ubelaker (1994) *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archeological Survey Research Series No. 44. Arkansas Archeological Survey, Fayetteville, AR.

Byers, S. N. (2008) *Introduction to Forensic Anthropology* (3rd ed.). Pearson Education, Boston.

Cain, C. R. (2005) Using burned animal bone to look at Middle Stone Age occupation and behavior. *Journal of Archaeological Science* 32(6):873–884.

Calce, S. E., and T. L. Rogers (2007) Taphonomic changes to blunt force trauma: A preliminary study. *Journal of Forensic Sciences* 52(3):519–527.

Cardoso, H. F. V., A. Santos, C. Garcia, M. Pinto, C. Sérgo, and T. Magalhaes (2010) Establishing a minimum postmortem interval of human remains in an advanced state of skeletonization using the growth rate of bryophytes and plant roots. *International Journal of Legal Medicine* 124:451–456.

Casamatta, D., and R. Verb (2000) Algal colonization of submerged carcasses in a mid-order woodland stream. *Journal of Forensic Sciences* 45(6):1280–1285.

Christensen, A. M., and S. W. Meyers (2011) Macroscopic observations of the effects of varying fresh water pH on bone. *Journal of Forensic Sciences* 56(2):475–479.

Cole, G., and T. Waldron (2016) Purple staining of archaeological human bone: An investigation of probable cause and implications for other tissues and artifacts. *Journal of Anthropology* 2:1–11.

Cope, D. J., and T. L. Dupras (2009) The effects of household corrosive chemicals on human dentition. *Journal of Forensic Sciences* 54(6):1238–1246.

Courty, M. A., R. Goldberg, and R. Macphail (1989) *Soils and Micromorphology in Archaeology.* Cambridge University Press, Cambridge, MA.

Coyle, H. M. (2004) Plant diversity. In *Forensic Botany: Principles and Applications to Criminal Casework* ed. by H. M. Coyle, pp. 81–96. CRC Press, Boca Raton, FL.

Cronyn, J. M. (1990) *The Elements of Archaeological Conservation*. Routledge, London.

Cukrowska, E. M., T. S. McCarthy, S. Pole, L. Blackwell, and C. Steininger (2005) The chemical removal of manganese dioxide coatings from fossil bones from the cradle of humankind, South Africa. *South African Journal of Science* 101:101–103.

Cutler, A. H., A. K. Behrensmeyer, and R.E. Chapman (1999) Environmental information in a recent bone assemblage: Roles of taphonomic processes and ecological change. *Palaeogeography, Paleoclimatology, Paleoecology* 149:359–372.

Davies, K. (2004) An introduction to plant pigments in biology and commerce. In *Plant Pigments and Their Manipulation* ed. by K. Davies, pp. 1–22. Annual Plant Reviews, Vol. 14. Blackwell Publishing, Oxford.

Dupras, T. L., J. J. Schultz, S. M. Wheeler, and L. J. Williams (2011) *Forensic Recovery of Human Remains: Archaeological Approaches* (2nd ed.). CRC Press, Boca Raton, FL.

Edwards, R. (1996) The effect of changes in groundwater geochemistry on the survival of buried metal artefacts. In *Preserving Archaeological Remains in situ* ed. by M. Corfield, P. Hinton, T. Nixon, and M. Pollard, pp. 86–92. Museum of London Archaeology Service, London.

Emsley, J. (2001) *Nature's Building Blocks: An A-Z Guide to the Elements.* Oxford University Press, Oxford.

Fenton, T. W., W. H. Birkby, and J. Cornelison (2003) A fast and safe non-bleaching method for forensic skeletal preparation. *Journal of Forensic Sciences* 48(1):274–276.

Fitzpatrick, R. W. (2008) Nature, distribution and origin of soil materials in the forensic comparison of soils. In *Soil Analysis in Forensic Taphonomy: Chemical and Biological Effects of Buried Human Remains* ed. by M. Tibbett and D. O. Carter, pp. 1–28. CRC Press, Boca Raton, FL.

Galloway, A. (1997) The process of decomposition: A model from the Arizona-Sonoran Desert. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W.D. Haglund and M.H. Sorg, pp. 139–150. CRC Press, Boca Raton, FL.

Galloway, A., W. H. Birkby, A. M. Jones, T. E. Henry, and B. O. Parks (1989) Decay rates of human remains in an arid environment. *Journal of Forensic Sciences* 34(3):607–616.

Goffer, Z. (2007) *Archaeological Chemistry.* Wiley, Hoboken, NJ.

Gruspier, K. L. (1999) Pathological changes in human skeletal remains: Before, during or after? *In Forensic Osteological Analysis: A Book of Case Studies* ed. by S. I. Fairgrieve, pp. 199–225. Charles C Thomas, Springfield, IL.

Guthrie, R. D. (1990) *Frozen Fauna of the Mammoth Steppe: The Story of Blue Babe.* University of Chicago Press, Chicago.

Haefner, J. N., J. R. Wallace, and R. W. Merritt (2004) Pig decomposition in lotic aquatic systems: The potential use of algal growth in establishing a postmortem submersion interval (PMSI). *Journal of Forensic Sciences* 49(2):330–336.

Haglund, W. D., M. Connor, and D. D. Scott (2002) The effect of cultivation on buried human remains. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 133–150. CRC Press, Boca Raton, FL.

Hall, D. W. (2012) Plants as evidence. In *Forensic Botany: A Practical Guide* ed. by D. W. Hall and J. H. Byrd, pp. 12–44. John Wiley and Sons, Oxford.

Hallingbäck, T., and N. Hodgetts (2000) *Mosses, Liverworts, and Hornworts: Status Survey and Conservation Action Plan for Bryophytes*. IUCN/SSC Bryophyte Specialist Group, Cambridge.

Hardy, C. R., and J. R. Wallace (2012) Algae in forensic investigations. In *Forensic Botany: A Practical Guide* ed. by D. W. Hall and J. H. Byrd, pp. 145–173. Wiley, Oxford.

Hartnett, K. M., L. C. Fulginiti, and F. Di Modica (2011) The effects of corrosive substances on human bone, teeth, hair, nails, and soft tissue. *Journal of Forensic Sciences* 56(4):954–959.

Holland, T. D., B. E. Anderson, and R. W. Mann (1997) Human variables in postmortem alteration of human bone: Examples from U.S. war casualties. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 263–274. CRC Press, Boca Raton, FL.

House, J. E. (2008) *Inorganic Chemistry*. Academic Press, Burlington, MA.

Huculak, M. A., and T. L. Rogers (2009) Reconstructing the sequence of events surrounding body disposition based on color staining of bone. *Journal of Forensic Sciences* 54(5):979–984.

Janaway, J. C. (2008) The decomposition of materials associated with buried cadavers. In *Soil Analysis in Forensic Taphonomy: Chemical and Biological Effects of Buried Human Remains* ed. by M. Tibbett and D. O. Carter, pp. 153–201. CRC Press, Boca Raton, FL.

Janjua, M. A., and T. L. Rogers (2008) Bone weathering patterns of metatarsal v. femur and the postmortem interval in southern Ontario. *Forensic Science International* 178:16–23.

Johanson, G. (1976) Iron from cannon balls in teeth and jaws. *Ossa* 3–4:183–187.

Joiner, A. (2006) The bleaching of teeth: A review of the literature. *Journal of Dentistry* 34(7): 412–419.

Komar, D. A. (1998) Decay rates in a cold climate region: A review of cases involving advanced decomposition from the Medical Examiner's Office in Edmonton, Alberta. *Journal of Forensic Sciences* 43(1):57–61.

Lee, E. J., J. G. Luedtke, J. L. Allison, C. E. Arber, D. A. Merriwether, and D. W. Steadman (2010) The effects of different maceration techniques on nuclear DNA amplification using human bone. *Journal of Forensic Sciences* 55(4):1032–1038.

Mairs, S., B. Swift, and G. N. Rutty (2004) Detergent: An alternative approach to traditional bone cleaning methods for forensic practice. *American Journal of Forensic Medicine and Pathology* 25(4):276–284.

Mann, R. W., M. E. Feather, C. S. Tumosa, T. D. Holland, and K. N. Schneider (1998) A blue encrustation found on skeletal remains of Americans missing in action in Vietnam. *Forensic Science International* 97:79–86.

Maples, W. R., and M. Browning (1994) *Dead Men Do Tell Tales: The Strange and Fascinating Cases of a Forensic Anthropologist*. Doubleday, New York.

Martill, D. M. (1991) Bones as stones: The contribution of vertebrate remains to the lithologic record. In *The Processes of Fossilization* ed. by S. K. Donovan. pp. 270–292. Columbia University Press, New York.

McGowan, G., and J. Prangnell (2006) The significance of vivianite in archaeological settings. *Geoarchaeology* 21(1):93–111.

McIntosh, J. (1999) *The Practical Archaeologist: How We Know What We Know About the Past* (2nd ed.). Checkmark Books, New York.

Millard, A. (1996) Bone in the burial environment. In *Preserving Archaeological Remains in situ* ed. by M. Corfield, P. Hinton, T. Nixon, and M. Pollard, pp. 93–102. Museum of London Archaeology Service, London.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pollard, M.A (1996) The chemical nature of the burial environment. In *Preserving Archaeological Remains in situ* ed. by. M. Corfield, P. Hinton, T. Nixon, and M. Pollard, pp. 60–65. Museum of London Archaeology Service, London.

Pollock, C. R., J. T. Pokines, and J. D. Bethard (2018). Organic staining on bone from exposure to wood and other plant materials. *Forensic Science International* 283:200–210.

Quatrehomme, G., and M. Y. İşcan (1997) Postmortem skeletal lesions. *Forensic Science International* 89:155–165.

Rennick, S. L., T. W. Fenton, and D. R. Foran (2005) The effects of skeletal preparation techniques on DNA from human and non-human bone. *Journal of Forensic Sciences* 50(5):1016–1019.

Richardson, G. M., R. Wilson, D. Allard, C. Purtill, S. Douma, and J. Graviere (2011) Mercury exposure and risks from dental amalgam in the US population, post-2000. *Science of the Total Environment* 409:4257–4268.

Schaetzl, R., and A. Anderson (2005) *Soils: Genesis and Geomorphology.* Cambridge University Press, New York.

Schafer, A. T. (2001) The colour of the human skull. *Forensic Science International* 117:53–56.

Schultz, J. J. (2012) Determining the forensic significance of skeletal remains. In *A Companion to Forensic Anthropology* ed. by D. Dirkmaat, pp. 66–84. Wiley-Blackwell, Oxford.

Schultz, J. J., A. E. Green, R. A. Murdock, M. H. Hansen, and J. D. Garavaglia (2020) The use of human skeletal remains in Palo rituals in Orange County, Florida. In *Case Studies in Forensic Anthropology: Bonified Skeletons* ed. by H. M. Garvin and N. R. Langley, pp. 255–268. CRC Press, Boca Raton, FL.

Schultz, J. J., M. A. Williamson, S. P. Nawrocki, A. B. Falsetti, and M. W. Warren (2003) A taphonomic profile to aid in the recognition of human remains from historic and/or cemetery contexts. *Florida Anthropologist* 56(2):141–147.

Schultz, J. J., M. M. Hawkins, and A. T. Alexander (2018) Skeletal weathering in central Florida: A preliminary approach for developing a scoring to estimate time since death. *Forensic Science International* 290:85–93.

Shahack-Gross, R., O. Bar-Yosef, and S. Weiner (1997) Black-coloured bones in Hayonim Cave, Israel: Differentiating between burning and oxide staining. *Journal of Archaeological Science* 24(5):439–446.

Siver, P. A., W. D. Lord, and D. J. McCarthy (1994) Forensic limnology: The use of freshwater algal community to link suspects to an aquatic crime scene in southern New England. *Journal of Forensic Sciences* 39(3):847–853.

Sledzik, P. S., and S. Ousley (1991) Analysis of six Vietnamese trophy skulls. *Journal of Forensic Sciences* 36(2):520–530.

Steadman, D. W., L. L. DiAntonio, J. J. Wilson, K. E. Seridan, and S. P. Tammariello (2006) The effects of chemical and heat maceration techniques on the recovery of nuclear and mitochondrial DNA from bone. *Journal of Forensic Sciences* 51(1):11–17.

Thali, M. J., B. Lux, S. Losch, F. W. Rosing, J. Hurlimann, P. Feer, R. Dirnhofer, U. Konigsdofer, and U. Zollinger (2011) "Brienzi"—The blue Vivianite man of Switzerland: Time since death estimation of an adipocere body. *Forensic Science International* 211:34–40.

U.S. Food and Drug Agency (USFDA) (2009) *White Paper: FDA Update/Review of Potential Adverse Health Risks Associated with Exposure to Mercury in Dental Amalgam*. USFDA, National Center for Toxicological Research, Washington, DC.

Ubelaker, D. H. (1996) The remains of Dr. Carl Austin Weiss: Anthropological analysis. *Journal of Forensic Sciences* 41(1):60–79.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–89. CRC Press, Boca Raton, FL.

Ubelaker, D. H., and K. M. Zarenko (2011) Adipocere: What is known after over two centuries of research. *Forensic Science International* 208:167–172.

Ubelaker, D. H., and N. D. Sperber (1988) Alterations in human bones and teeth as a result of restricted sun exposure in contact with corrosive agents. *Journal of Forensic Sciences* 33(2):540–548.

Wetli, C. V., and R. Martinez (1981) Forensic sciences aspects of Santeria, a religious cult of African origin. *Journal of Forensic Sciences* 26(3):506–514.

White, T., and P. Folkens (1991) *Human Osteology*. Academic Press, San Francisco.

Wiley, P., and P. Leach (2009) The skull on the lawn: Trophies, taphonomy, and forensic anthropology. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 179–189. Prentice Hall, Upper Saddle River, NJ.

Winburn, A. P., S. K. Schoff and M. W. Warren (2016) Assemblages of the dead: Interpreting the biocultural and taphonomic signature of Afro-Cuban Palo practice in Florida. *Journal of African Diaspora Archaeological Heritage* 5(1):1–37.

Zayat, M., P. Garcia-Parejo, and D. Levy (2007) Preventing UV-light damage of light sensitive materials using a highly protective UV-absorbing coating. *Chemical Society Reviews* 36(8):1270–1281.

Zimmerman, K. A., and J. R. Wallace (2008) The potential to determine a postmortem submersion interval based on algal/diatom diversity on decomposing mammalian carcasses in brackish ponds in Delaware. *Journal of Forensic Sciences* 53(4):935–941.

Taphonomy and the Timing of Bone Fractures in Trauma Analysis

13

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Contents

> To die nameless and be put away in some no man's land where the relics are as shadows. Bone orchard just beyond the outer limits of the city where sense peters away in vacancy and evening will have the feathers of ravens. A passer-by may be out for a walk, stop here or there, bring a hand to her brow, try to imagine. She has a dog with her sniffing at the soil. How to unriddle faded runes, memory gone? How can she know? What is there to know?
>
> **—Breytenbach (2008:12)**

Introduction

The cause of bone fractures is a difficult assessment and has larger implications and repercussions, particularly when a forensic anthropologist is tasked with differentiating human-induced injuries relevant to the cause and manner of death from either geological

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or biological alterations (Nawrocki 2009; Sorg 2019). The latter is often classified as *pseudotrauma* and is defined as an alteration to wet/fresh skeletal remains that appears to be human-induced but in fact has natural origins. *Wet* or *fresh* bone is defined as retaining moisture and organic contents (including water and lipid), whereas *dry* bone lacks an organic component (primarily collagen) and experiences degradation. These processes are a consequence of an increase in the postmortem interval (PMI) and exposure of the remains to environmental circumstances (Cattaneo et al. 2017; Green and Schultz 2017; Kemp 2016; L'Abbé et al. 2015; Wescott 2019). The exact time of change from wet to dry bone is not straightforward and varies greatly with depositional context (e.g., Dirkmaat and Adovasio 1997; Hill 1980; Nawrocki 2009; Sorg 2019).

Archaeologists routinely discuss fracture characteristics of wet and dry bone as a means to differentiate human-induced butchery practices from other taphonomic influences (Biddick and Tomenchuk 1975; Hill 1980; Johnson 1985; Morlan 1984). Biological anthropologists are also interested in deciphering culturally induced modifications to bone from other terrestrial (see Chapter 9, this volume) and marine (Chapter 7) animal alterations, water abrasion (Chapters 6 and 7), and plant action (Chapters 5 and 12). Furthermore, unintentional human alterations such as plowing and cemetery burial (Chapter 5) and excavation itself (Chapter 17) also may alter bones in ways that could be erroneously mistaken for fatal injuries. Thus, accurate assessment of the timing of a traumatic injury is paramount when establishing the sequence of events at a crime scene and in determining whether a crime was committed.

In the anthropological literature, the timing of an injury—perimortem or postmortem—is often used simultaneously to explain the death event (Cappella et al. 2014; Cattaneo et al. 2017; Galloway 1999; Komar and Buikstra 2008; Sauer 1998). The anthropologist, however, describes all injuries occurring to wet/fresh bone as perimortem, despite the fact that somatic death already occurred (Cattaneo et al. 2017; Kemp 2016). The latter is the purview of a forensic pathologist whose definition of the perimortem interval is purely based on somatic death, not bone degradation (Cattaneo et al. 2017; Cattaneo and Cappella 2017; Cunha and Pinheiro 2009). The problem with the definition of perimortem for bone is that researchers are "unclear what exactly constitutes near death in terms of skeletal modifications" (Cattaneo et al. 2017:174).

Instead of focusing on the death event, forensic anthropologists need to provide a description of the bone fracture that is associated with the bone's condition (wet or dry) at the time of injury and within the context of the scene recovery (L'Abbé et al. 2015; Kemp 2016). For example, bone trauma that immediately follows death, such as dismemberment or burning, occurs while the bones are fresh; thus, the bone responds as fresh bone does to injury. While damage to dry bone may be easily recognizable (such as rodent gnawing or obvious color differentiation between outer and inner cortical layers), the circumstances surrounding a bone fracture are more difficult to infer without information on scene context. Thus, any direct association between the timing of a bone injury and the cause/manner of death should only be made with knowledge of the scene or the recovery process (Dirkmaat et al. 2008; Dirkmaat and Adovasio 1997; L'Abbé et al. 2015, 2019; Nawrocki 2009; Sorg 2019).

Variability is the rule, not the exception, in both taphonomic and bone trauma analysis. Similar to the biological profile used to estimate age, sex, ancestry, and stature, a taphonomic profile is compiled as a means to interpret the circumstances surrounding death and recovery (Nawrocki 2009; Nawrocki et al. 1997; Sorg 2019). According to

Nawrocki (2009:288), a taphonomic profile is "a set of hypotheses regarding the perimortem and postmortem history of the remains, drawn from a detailed description of the condition of the bones, soft tissues and the immediate recovery site". In order to create this profile, three main influences are addressed: cultural/assailant behavior, biotaphonomy, and geotaphonomy (Nawrocki 2009; Nawrocki et al. 1997). Cultural behavior (Chapter 10) refers to the assailant's altering the environment such as digging a hole, dragging the body, or throwing the body into a ravine. The assailant's actions are likewise dependent on his or her skill/strength in disposing of human remains and in the intrinsic characteristics of the victim such as mass and body position. Biotaphonomy addresses both intrinsic (e.g., decomposition) and extrinsic modifications (e.g., carnivore activity) to a victim. The influences from the geological environment on the assailant, the victim, and the location of the body are referred to as geotaphonomy (Nawrocki 2009). When all of these relationships are examined in situ, the death event can be more objectively (and ultimately, scientifically) interpreted with an anthropologist obtaining a clearer picture as to the cause of death and any possibly traumatic injuries associated with the death (Sorg 2019).

The aim of this chapter is to describe basic biomechanics and fracture characteristics of wet and dry bone. With the use of a case study, the authors emphasize the complexities of deciphering wet- and dry-bone fractures and associate the correspondence of these interpretations to a sequence of events. Even a complete skeleton may not be informative enough to assist a forensic pathologist in the interpretation of cause or manner of death; more in-depth interpretations may be achieved with the knowledge gained from scene context. Furthermore, the authors stress the need for anthropologists to recognize the biomechanical processes associated with each bony response for accurate fracture pattern interpretations and trauma analyses.

Bone Biomechanics: Basic Terminology

Bone biomechanics, in general, and wet and dry bone, specifically, can be explained with the use of Young's Modulus of Elasticity and stress–strain curves for any material (Figure 13.1) (Currey 2002; Frankel and Nordin 2001; Kemp 2016; L'Abbé et al. 2015, 2019; Özkaya and Nordin 1999; Scheirs et al. 2018; Wescott 2019). Young's Modulus of Elasticity is used to test the strength, or stiffness, of a material with a known stress (tensile, compressive, or shear) and rate of loading. The *strength* of any material is the amount of energy that material can absorb prior to deformation. *Stress* is calculated as force divided by surface area and is often expressed in N/m^2 or lbf/in^2 (Low and Reed 1996). *Strain* is the elastic deformation of a material under a known stress and rate of load (Harkess and Ramsey 1996; Tencer 2006). A stress–strain curve measures the point of resistance to the point of failure and is calculated by the change in length (mm) divided by the original length (mm) (Currey 2002; Low and Reed 1996).

Young's Modulus of Elasticity and stress–strain curves illustrate two distinctly different concepts. Young's Modulus, or Modulus of Elasticity, is the strength (stiffness) of a material. The stress–strain curve goes on to describe plastic strain and the eventual failure of a material. As expected, only materials that contain elastic properties can deform; in less elastic materials, such as glass and dry/burned bone, failure occurs quickly after surpassing the ultimate strength threshold (L'Abbé et al. 2015, 2019; Wescott 2019).

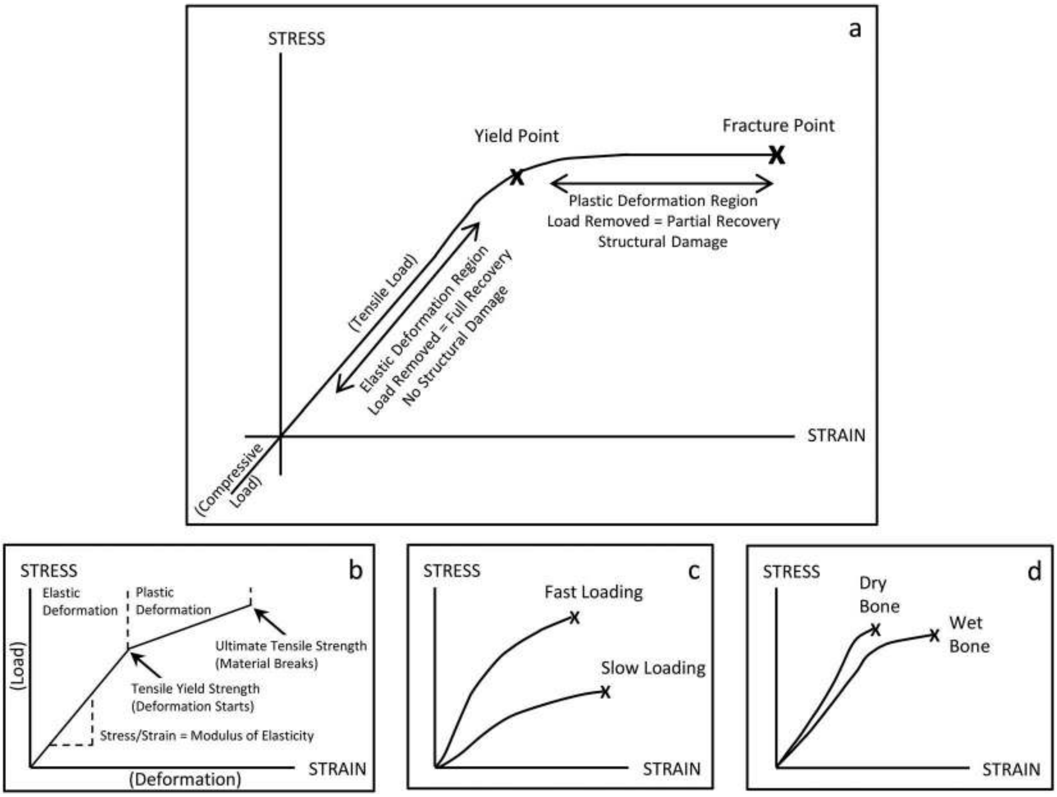

Figure 13.1 Four examples of Young's Modulus and stress–strain curves: (a) a general stress–strain curved created for illustration and descriptive purposes (not associated with any particular type of material); the small "X" on the left represents the yield point and transition from the elastic phase to the plastic phase, and the larger "X" on the right represents the fracture point; (b) bone stress vs. strain; (c) fast vs. slow-loaded bone; and (d) wet vs. dry bone; (a) adapted from Symes et al. (2012:347); (b) adapted from Galloway (1999:38); (c) adapted from Özkaya and Nordin (1999:208); and (d) adapted from Özkaya and Nordin (1999:210).

In Figure 13.1, Young's Modulus of Elasticity and stress–strain curves for different materials, different loads, and different bone conditions are illustrated. The area under the curve demonstrates the ductility of a material and essentially refers to the ability to deform, or undergo a greater strain prior to failure (Christensen et al. 2018; Currey 2002). A stress–strain curve is presented and is not associated with any particular type of material in Figure 13.1a. Various stress–strain curves for bone are located beneath this image. When stress and strain are in proportion, the material maintains a normal shape and is within the strength levels for Young's Modulus of Elasticity (a). When stress and strain produce a straight line, elastic deformation (i.e., Young's Modulus) occurs and is recoverable. If stress exceeds strain (stress–strain curve), and the material reaches the *yield point*, even if stress is removed, the material is unable to return to its normal shape and has been subjected to forces above the material's elastic limits (Currey 2002; Low and Reed 1996; Reilly and Burstein 1974). When stress is removed and the material remains deformed, it has entered the plastic phase of deformation (b). In this phase, the material is compromised, even if it is only detectable at the microscopic level, and any additional stress may cause the material to fail completely. Anthropologists need to remember that all strain modes—tension, compression, and shear—act simultaneously to produce a bone fracture. Fracture morphology is attributed to a complex interaction of tension, compression, and shear forces that can be loaded in a quasi-static (slow) or dynamic (rapid) manner (L'Abbé et al. 2015, 2019; Symes et al. 2012; Thornton and Cashman 1986).

Biomechanics and Bone Structure

Bone, comprised of organic and inorganic material, serves to support the body, to protect internal organs, to anchor muscles, and to assist in movement (Currey 2002; Low and Reed 1996; Pierson and Lieberman 2004; Tencer 2006). At the microscopic level, bone tissue contains organic collagen fibers imbedded within inorganic crystals of calcium hydroxyapatite, a combination that provides strength, density, and elasticity. Living bone contains 65%–70% organic and 25%–30% inorganic materials (Pierson and Lieberman 2004).

When considered as a material, bone is nonhomogeneous, anisotropic, viscoelastic, and brittle (Currey 2002; Özkaya and Nordin 1999; Reilly and Burstein 1974; Tencer 2006). Nonhomogeneous refers to gross types and shapes of bone (e.g., skull vs. femur), the location and surface of a bone (e.g., proximal vs. midshaft), the structure of bone (e.g., cortical vs. trabecular or spongy), and the microstructure of bone (e.g., apatite [biphasic]) (Currey 2002; Özkaya and Nordin 1999; Tencer 2006). As bone is nonhomogeneous, the material also presents with an anisotropic response to a mechanical load. Anisotropic implies that the mechanical properties of a long bone respond with different strengths when loaded in different directions (Currey 2002; Frankel and Nordin 2001; Özkaya and Nordin 1999). The structural foundation and remodeling abilities in a long bone follow a longitudinal pattern (primary and secondary osteons); these structures enhance long bone strength in axial loads—similar to rebar inserted into concrete—but offer less resistance to failure in angled or perpendicular impacts (Currey 2002; Frankel and Nordin 2001; Özkaya and Nordin 1999). Therefore, the differential resistance of long bones to directional stress is an important variable to consider in any bone trauma analysis.

Each skeletal element is adapted to perform a certain mechanical function in the body, which also contributes to its specific anisotropic response. For example, the femur supports the body's weight, while the radius is responsible for lifting, hanging, and carrying objects. When the two bones are biomechanically tested for tensile and compressive strength along a longitudinal plane, the femur presents with weaker tensile strength and greater compressive strength than the radius (Reilly and Burstein 1974). Therefore, the strength and corresponding strain of a bone in response to an applied force (tensile, compressive, and shear) are also directly dependent on the function of that bone within the skeletal structure (Currey 2002; Reilly and Burstein 1974). Simply defined, *anisotropy* refers to the varying response a bone has to external stress due to the intrinsic qualities and function of each bone within the skeletal structure. For this reason, the type of bone, the location of a traumatic injury, and the direction of force have important implications for interpreting the mechanism of injury. Anisotropy becomes important in differentiating fractures potentially associated with cause and or manner of death from fractures associated with biological or environmental causes. The practitioner needs to assess whether a pattern of injury can be observed throughout the skeleton (or skeletal fragments) and whether these patterns are consistent with the environmental context of discovery and recovery (L'Abbé et al. 2015; Sorg 2019).

Viscoelastic refers to the bony response to the length of time and the rate of speed at which an external load is placed (Currey 2002; Özkaya and Nordin 1999). In order to understand the mechanism of fracture and fracture morphology, an important determinant to consider is speed (Hansen et al. 2008; Symes et al. 2012; Zioupos et al. 2008). With moving objects, kinetic energy is equal to one-half the mass of the object multiplied by the velocity of the object squared ($1/2\ mv^2$). A fracture occurs when a bone can no longer absorb energy from either a slow-loaded force, such as a car bumper to the tibia (mph), or a fast-loaded force (fps), such as a bullet.

When a slow-loaded force is applied to bone and then removed before failure, bone can respond by bending and then return to its original shape. If the slow-loaded force continues, the bone may not recover, and it will plastically deform (presents with ductility) and eventually fail (Figure 13.1) (e.g., L'Abbé et al. 2015, 2019). With a rapid-loaded force, bone immediately absorbs a greater amount of energy, is unable to mechanically bend due to the rapid stress (does not experience ductility), becomes resistant, and shatters (e.g., Berryman and Symes 1998; Hansen et al. 2008; Matrille and Symes 2019; Scheirs et al. 2018; Smith et al. 1987; Symes et al. 1996, 2012; Thornton and Cashman 1986; Zioupos et al. 2008).

External forces are usually classified into magnitude, duration, and rate. When focusing on speed (mph and fps), the ductile vs. brittle response of bone is revealed and manifested within fracture production. Fractures associated with slow-loaded forces are often linear (less fractures) and exhibit visible tension and compression, whereas fractures associated with rapid-loaded forces are comminuted and exhibit failure due to high-energy absorption (more fractures). For a complete explanation of slow- and fast-loaded bone trauma classifications, see Berryman and Symes (1998), L'Abbé et al. (2015, 2019), Matrille and Symes (2019), Smith et al. (1987), and Symes et al. (2012).

Microstructure of bone is also an important determinant in fracture production and morphology. Skeletal elements of white-tailed deer (*Odocoileus virginianus*), pig (*Sus scrofa*), and cattle (*Bos taurus*) have been used to simulate fracture morphology and fracture patterns to different forces, weapons, and environmental conditions (Calce and Rogers 2007; de Gruchy and Rogers 2002; Green and Schultz 2017; Janjua and Rogers 2008; Wieberg and Wescott 2008). However, the nonhomogeneous and anisotropic features of bone preclude analogizing fracture morphology and mechanism of fracture of nonhuman bone to human material (Green and Schultz 2017; Hansen et al. 2008; Keller et al. 1990; Scheirs et al. 2018). Skeletal systems evolved to serve the mechanical needs of each species, particularly with regard to compressive strength and strain, so the biomechanical response to an external force is considered species- or at least genus-specific.

Furthermore, many domestic animals utilized in bone trauma research are subadults at the age of slaughter, which further confounds the issue of interpreting fracture patterns. Since the distribution and structural foundation of primary and secondary osteons differ considerably between subadults and adults and differ within and between species (Pierson and Lieberman 2004), differences in strength and strain modes (tension, compression, and shear) will also exist, affecting the mechanism of fracture and overall fracture morphology. For these reasons, many researchers have recently advocated for the use of human bone during experimental fracture studies (e.g., Cattaneo and Cappella 2016; Isa 2020; Ribeiro et al. 2020; Scheirs et al. 2017 2018, 2019, 2020).

Biomechanics of Wet and Dry Bone

In research on the tensile strength of dry and wet human long bones, Reilly and Burstein (1974:38) observed less tensile strength and higher tensile strain in wet bone when compared to dry bone (see Figure 13.1b). Simply stated, wet bone is stiff and elastic, while dry bone is stiff and brittle (e.g., L'Abbé et al. 2015; Wescott 2019). The reason is due to the loss of viscoelastic properties in dry bone, which will not necessarily affect a bone's strength, or Young's Modulus of Elasticity, but will lessen a bone's ability to undergo strain (Özkaya and Nordin 1999; Reilly and Burstein 1974). Without viscoelasticity, the fracture mechanism of dry bone differs, as it is not able to withstand as much strain as wet bone and immediately fractures soon after the ultimate strength threshold is reached. Like wet bone, dry bone also fails in tension, shear, and compression, but the bone's responses to these stresses are almost simultaneous (Ubelaker and Adams 1995; L'Abbé et al. 2015, 2019). The fact that bone does not degrade in a prescribed manner makes it impossible to interpret bone plasticity (wet or dry) without environmental context of discovery and recovery of the remains (Sorg 2019).

Many of the earlier examples only explain strength differences of wet and dry bone in one stress mode—tension. In order to distinguish wet- and dry-bone fractures, information on both tensile and compressive strength/strain is necessary. Under pure tensile stress, both wet and dry bone split apart, and osteons are torn from Haversian systems (Hentschel 2014; Pechníková et al. 2011); in macroscopic cross-section, the surface area of the bone appears mottled. As dry bone merely fractures quicker than wet bone under tensile stress, no distinctly obvious fracture differences should be observed between the two conditions.

Compressive (bending) stress is perhaps more easily observable than tensile stress in fracture morphology on wet and dry bone. Due to the elasticity in wet bone, it can resist compressive strain almost two times longer than either tensile or shear strains (Frankel and Nordin 2001; Harkess and Ramsey 1996; Hildebrand and Goslow 2001; Özkaya and Nordin 1999). For this reason, the degree of bending and the subsequent appearance of fracture morphology differ between wet and dry bone, as the latter is less ductile (e.g., Ribeiro et al. 2020; Scheirs et al. 2017, 2018, 2019, 2020). Recently, in a comprehensive examination of long bone fracture patterns, Isa (2020) found that trait characteristics for tension (mottled bone, osteon pull-out) and compression (crushing with ridges and valleys) were highly repeatable on cortical bone (fractured femora).

Fracture Characteristics for Distinguishing Wet and Dry Bone

Multiple features have been used to differentiate fracture patterns on wet and dry bones, namely: color; fracture outline, angle, surface; and termination of radiating fractures (Karr and Outram 2012b; LaCroix 2013; Morlan 1984; Shattuck 2010; Wheatley 2008; Wieberg and Wescott 2008).

Color

Differences in color on the external and internal surfaces of cortical bone are reliable in distinguishing the timing of a fracture (Dirkmaat and Adovasio 1997; Ubelaker and Adams 1995). Taphonomic processes, such as soil and decompositional staining, sun-bleaching, and root etching, influence the external surface differently, or at a different rate, then the internal surface of bone (Berryman et al. 1991; Nawrocki 2009; see also Chapters 5, 11,12, and 20). Therefore, any fracture subsequent to deposition will present with a color differentiation between the old and newly exposed bone surfaces.

However, the opposite is not true. A homogeneous distribution of color on the external and internal cortical bone surfaces does not always imply a perimortem injury; further information about the deposition of the material such as a primary or secondary burial is needed (Johnson 1985; L'Abbé et al. 2015; Morlan 1984; Sorg 2019; Ubelaker and Adams 1995). Bones can be altered prior to deposition, during interment, or during excavation (Morlan 1984; Sorg 2019). For example, a bone is broken prior to a deliberate or accidental reinternment. During reinternment, the external and cross-sectional cortical surface of the broken bone acquires a homogeneous color. Without recovery context or observation of additional fracture morphology characteristics, an absence of color differences may not be useful to the anthropologist in evaluating wet vs. dry timing of a fracture (Kemp 2016; L'Abbé et al. 2015; Sorg 2019).

Fracture Morphology: Outlines, Angles, and Edges

In an attempt to quantify fracture morphology, anthropologists have categorized wet and dry long bone fractures into three categories: outline, angle, and edge (surface). Outline refers to the general appearance of the fracture lines (i.e., round for a perpendicular angle verses oval for an acute/obtuse angle); angle refers to the slope between the fracture surface and the bone, namely obtuse or acute for wet bone and perpendicular for dry; and surface refers to the roughness (jagged) or smoothness of the cross-sectional edges of the fracture (Johnson 1985). Anthropologists use fracture classifications such as these to describe discontinuities in fresh/wet bone, but dry bone is described as brittle with fractures lines that run along (longitudinal cracking) or perpendicular (transverse) to the grain of the bone (Wescott 2019, Figure 13.3). Wet bone is described as having curved or V-shaped fracture outlines (see Figures 13.2 and 13.3) (Galloway 1999; Shattuck 2010; Villa and Mahieu 1992).

Johnson (1985) and Einhorn (2005) noted acute/obtuse fracture angles on the surfaces of wet-bone and right-angled/perpendicular fractures on the surfaces of dry bone, whereas Morlan (1984) found acute/obtuse angles on both wet and dry bone and perpendicular angles on fossilized bone. Furthering the debate, Bonnichsen (1979) also noted perpendicular angles on wet bone. While no consistency in fracture angles has been observed between wet and dry bone, researchers generally note a trend in angled surfaces associated with wet bone and perpendicular surfaces associated with dry bone (e.g., Green and Schultz 2017; LaCroix 2013).

Fracture edge (surface) refers to the cross-sectional topography of the break surfaces and is considered smooth on wet bone and jagged and/or stepped on dry bone (Figures 13.2 and 13.3) (Bonnichsen 1979; Green and Schultz 2017; Morlan 1984; Villa and Mahieu 1992; Wieberg and Wescott 2008). Researchers noted that crack formation due to weathering (longitudinal cracking) in dry cortical bone prompts the formation of stepped fractures. As the fracture extends from the point of impact, the cracked cortical surface is interrupted and redirects the fracture's propagation (Honeycutt 2012; Shattuck 2010).

Cappella et al. (2014) tested the reliability and repeatability of fracture outline, angle and surface morphology on known perimortem (wet) and postmortem (dry) bone fractures. Using two trained observers, and six months between observations, these researchers

Figure 13.2 Perimortem breakage to fresh white-tailed deer (*Odocoileus virginianus*) bone. (From LaCroix 2013.)

recorded an error of 14.8%–37% for "perimortem" bone and 5.5%–14% error rate for "postmortem" bone. Most of the errors for differentiating between "wet" and "dry" fractures were on spongy (trabecular) bone. The outcome of this study emphasized the importance of knowing the environmental context of discovery and recovery of a body as well as charting total body trauma patterns for the skeletal remains (L'Abbé et al. 2015, 2019; Sorg 2019).

Figure 13.3 Postmortem breakage to dry white-tailed deer (*Odocoileus virginianus*) bone after 28 weeks of subaerial exposure. (From LaCroix 2013.)

Without context and an evaluation of a possible injury pattern, a practitioner will be limited, as shown in Cappella et al. 2014, in their interpretation of the both the timing and potential cause of a bone fracture.

Knowledge of both the biomechanics of a fracture and prior knowledge of an injury is paramount for accurate estimations of fracture timing and bone trauma interpretations. L'Abbé et al. (2019) used biomechanical plasticity (tension, compression, and shear) over fracture classification to reconstruct a patterned leg injury from a pedestrian vehicle accident. The authors acknowledged the importance of having prior knowledge about an injury, or at least contextual knowledge of the discovery and recovery, for improved fracture interpretation. Additional strength to the use of bone biomechanics in the interpretation of fracture propagation and timing can be found in Christensen et al. (2018). Those researchers applied terminology used in fractography, which is the study of fractured surfaces, to a suite of blunt force failures on femora. Fractography terminology addresses the fracture topography of compression and tension failures, and includes bone mirror (tension), arrest ridges (compression), bone hackle (shear/compression), wake features, and cantilever curl (breakaway notch). All traits were shown to be repeatable in describing failure in compression and tension of a long bone, were more visible with oblique lighting, and were best visualized in cortical bone. The use of standard fractography traits may be a good approach in the future to standardizing the evaluation of the timing of an injury from skeletal remains (Emrith et al. 2020; L'Abbé et al. 2019).

Scheirs et al. (2017, 2018, 2019, 2020) as well as Ribeiro et al. (2020) described several new traits used to describe wet-bone fracture outlines, angles, and morphology from the compression side of a fracture and include: undulated margin, flakes with matching flake defects, peel with peel defects, fissures, crushed margins, bridge, folds, bone scales, wave lines, and plastic deformation. The authors provided high accuracies, 87% for the cranium, in using a suite of 6–9 previously mentioned traits to distinguish between perimortem (wet) and postmortem (dry) failure (Ribeiro et al. 2020). The traits are aligned with the biomechanical plasticity of the bone, and the observed bony topography is a consequence of failure in wet, bending bone. Consistent with previous research (e.g., Hentschel 2014, Green and Schultz 2017), Scheirs et al. (2017, 2018, 2019, 2020) noted topographic fracture variation in response to failure between dry and wet bone. None of the traits, however, for cranium, ribs, or long bones in these studies were tested for repeatability.

Fracture Termination

The termination location of radiating fractures has also been considered a key to distinguishing wet or dry bone. Most researchers have observed radiating fractures terminating prior to or at the epiphyses in wet but not in dry bone (Karr and Outram 2012a; Morlan 1984). The composition of cancellous bone, which is found in the epiphyses and metaphyses, is approximately 500% more ductile than diaphyseal bone and is designed to absorb shock more effectively in a longitudinal direction (Currey 2002; Simon et al. 1972). Diaphyses are found to fragment more than epiphyses in both wet- and dry-bone samples (Karr and Outram 2012b).

One of the authors (ML) performed a study on weathering and the biomechanical responses of wet and dry bone over a 9-month period in an open microhabitat situated in a coastal environment in southeastern Massachusetts, USA (LaCroix 2013). The breakage patterns and the minimal force required to fracture bone were specifically analyzed.

Table 13.1 Summary of Breakage Experiment of White-Tailed Deer (*Odocoileus virginianus*) Long Bones (n = 31) over 0–28 Weeks of Surface Exposure

Element	Mass (g)	Weeks Exposed	Force (lbs.)	Fracture Type	No. Frags.	Fracture Lines	Fracture Angle	Shape of Broken Ends	Fracture Surface Texture	Weathering Stage
Humerus	197.8	0	2000+	Spiral	11	Present	Sharp	Curved	Smooth	0
Humerus	230.3	0	1205	Oblique	8	Present	Sharp	Curved	Smooth	0
Humerus	206.5	0	1140	Comminuted	20	Present	Sharp	Curved	Smooth	0
Femur	229.7	6	1382	Butterfly	7	Present	Mixed	Curved	Smooth	0
Tibia	228.8	6	1826	Segmental	11	Present	Sharp	Curved	Smooth	0
Tibia	199.3	6	342	Oblique	9	Present	Sharp	Curved	Smooth	0
Femur	217.3	6	1570	Segmental	13	Present	Sharp	Curved	Smooth	0
Femur	229.5	6	1382	Segmental	7	Absent	Mixed	Curved	Smooth	0
Tibia	210.5	6	1800	Comminuted	15	Present	Mixed	Curved	Smooth	0
Tibia	225.6	10	902	Oblique	0	Present	Sharp	Curved	Smooth	0
Femur	219.2	10	744	Oblique	3	Present	Sharp	Curved	Smooth	0
Femur	214.7	10	2000+	Comminuted	12	Present	Mixed	Curved	Smooth	0
Tibia	201.9	10	681	Transverse	0	Present	Mixed	Jagged	Smooth	0
Tibia	182.4	15	2000+	Segmental	10	Present	Mixed	Jagged	Smooth	0
Femur	198.2	15	355	Spiral	2	Present	Mixed	Curved	Smooth	0
Tibia	239.4	15	2000+	Segmental	9	Absent	Sharp	Jagged	Smooth	0
Femur	192.3	15	233	Oblique	2	Present	Mixed	Jagged	Smooth	0
Tibia	206.1	15	529	Oblique	0	Absent	Sharp	Curved	Smooth	0
Tibia	218.6	20	770	Butterfly	3	Present	Mixed	Curved	Smooth	0
Tibia	174.6	20	639	Segmental	4	Present	Mixed	Jagged	Smooth	0
Humerus	173.5	20	2000+	Oblique	20	Present	Mixed	Jagged	Rough	0
Humerus	136.1	24	889	Butterfly with torsion	3	Present	Sharp	Curved	Rough	0
Humerus	152.7	24	888	Transverse	2	Present	Mixed	Transverse	Rough	0
Humerus	133.2	24	843	Transverse	2	Present	Sharp	Curved	Smooth	0
Humerus	125.3	24	892	Segmental	3	Present	Right	Curved	Rough	1
Humerus	165.4	24	782	Oblique	5	Present	Mixed	Jagged	Rough	0
Tibia	180.3	28	2000+	Segmental	13	Absent	Mixed	Jagged	Smooth	0
Femur	192.5	28	448	Butterfly	5	Absent	Mixed	Curved	Smooth	0
Humerus	180.5	28	346	Butterfly	1	Present	Right	Curved	Smooth	0
Humerus	249.5	28	1191	Segmental	2	Present	Mixed	Curved	Smooth	0
Humerus	178.5	28	399	Oblique	1	Present	Mixed	Curved	Smooth	0

Source: LaCroix (2013).

Results revealed trends similar to other experimental studies (Table 13.1); an increase in PMI and a loss of bone moisture were directly associated with morphological variation in the fracture outline, angle, and surface (Green and Schultz 2017; LaCroix 2013; Wheatley 2008; Wieberg and Wescott 2008). With an increase in PMI, smooth fracture surfaces, obtuse or acute angles, and curved/V-shaped outlines slowly changed to jagged surfaces, more right angles, and fewer curved fractures (LaCroix 2013; Wheatley 2008; Wieberg and Wescott 2008). Most studies note a significant decrease in bone moisture after two months, followed with a plateau phase, and a subsequently slower rate of drying (Wieberg and Wescott 2008; Green and Schultz 2017). Similarly, Shattuck (2010) observed dry transverse fractures after 42 days PMI, jagged fractures after 70 days PMI, and other dry bone characteristics after five months PMI.

Biomechanics and Fracture Characteristics

Differences in fracture morphology of wet and dry bones are directly attributed to the biomechanical response of the fleshed/fresh bone verse dry skeletal material to a load (stress). Forces applied to wet and dry bone may be identical, but bending features are expected to differ. Essentially, ductile wet bone demonstrates a resistance to bending, where fractures and microfractures appear and adjust, particularly to crushing and shearing. The adjustments in bending bone transitions create sharp edges and notches that represent failure, adjustment to force, and finally complete failure. Dry bone is brittle, and while diagnosis of tension and compression are possible, they are not dynamic in the plastic phase and essentially show complete failure at the yield point, as opposed to being able to resist strain in predictable manners. Dry bone fails easier in shear with few microfractures or readjustments when maximum stress is reached. According to Johnson (1985), dry-bone fractures "exhibit horizontal tension failure" such that the bone is transversely split on the longitudinal axis and produces right angles in cross-section (e.g., fracture surfaces).

Bone deformation is "dependent upon many factors including the magnitude, direction, and duration of the applied force, the material properties of the object, the geometry of the object, and the environmental factors such as heat and humidity" (Özkaya and Nordin 1999:127). The greatest predictor for fracture morphology in wet bone is speed of load, whereas in dry bone it is the lack of elasticity of the material. The elastic component of a bone, however, cannot be easily evaluated from its gross morphology, which is the likely reason for a high percentage of errors in distinguishing wet- and dry-bone fractures in Cappella et al (2014). For example, an elastic response has been noted on a seemingly dry bone (Ubelaker and Adams 1995). Karr and Outram (2012b) addressed the speed of moisture loss in varying climates and noted that bone degraded and dried much faster in hot, dry climates than in wet, cold climates. Like any decomposition process, bone degradation is highly variable and is not easily predicted (LaCroix 2013; Sauer 1998; Wescott 2019). The bone structure and the compositional properties do not change at an exact time; rather, they are gradual processes dependent on the environment and human intervention.

Most wet and dry experimental studies have been conducted on long bones. Human long bones are tubular with relatively thick cortical bone and less spongy bone in the shaft. When a stress is applied to a long bone, the tubular shaft maintains its shape until the point that stress exceeds strain and the bone bends plastically. As a bone bends, compressive and tensile strains tend to act on opposite sides of the bone (Figure 13.4) (Tencer 2006). As bone usually resists compressive strain longer than tensile strain, the bone fails transversely in tension, and the fracture assumes a steeper oblique orientation as the failure approaches pure compression (Berryman et al. 1991; L'Abbé et al. 2019; Symes et al. 2012). The cross-sectional morphology of these fractures is reminiscent of a butterfly and is colloquially described as a *butterfly fracture* with the triangular piece being referred to as a butterfly fragment (Lee et al. 2004). In butterfly fractures, the body represents tension and the wings indicate compression, and these can be used to ascertain the direction in which the bone bent (L'Abbé et al. 2015, 2019; Symes et al. 2012, 2013). As always, the true direction of bending is indicated by examining pure tension and maximum compression.

The characteristic microscopic features of a butterfly fracture include a bone tear, a breakaway spur or notch, possibly minor fracture lines for strain adjustment, and an area of shear between tension and compression. Bone tears can be noted on the tension

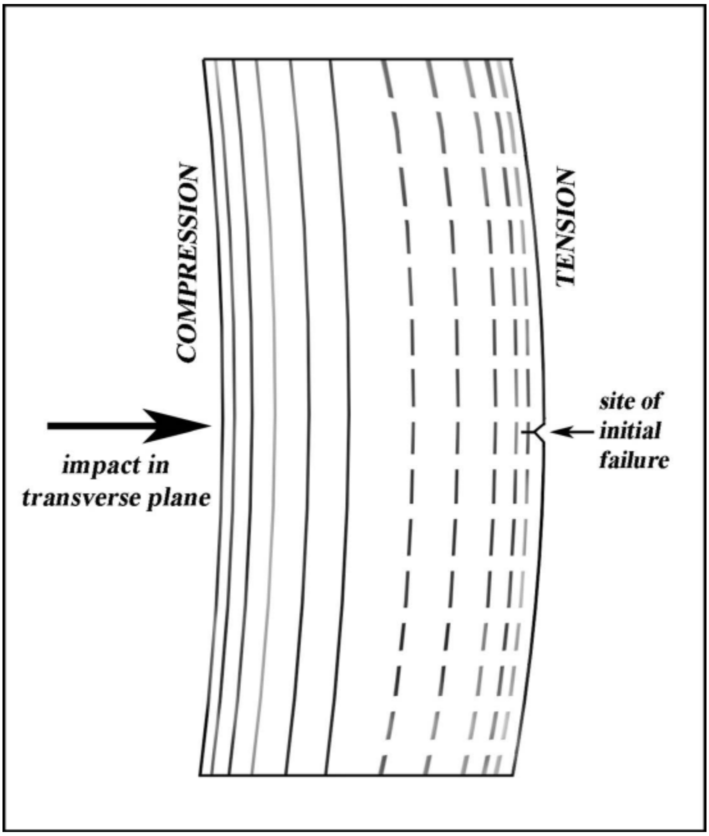

Figure 13.4 When a transverse force is applied perpendicularly to the shaft of a long bone, compression occurs on the side of the impact, while tension is occurring on the opposite side. (For simplification purposes, a solid cylinder is shown to depict areas of stress.) The lines drawn within the cylinder represent the paths followed by units of force as they pass through the object. The solid lines represent compression lines, while the dashed lines represent tension lines. (Illustration courtesy of Erin N. Chapman.)

side where the fractured bone surface appears mottled and billowy. Breakaway spurs and notches are jagged in appearance with at least one bone fragment exhibiting a "dog-eared" notch, where the bone likely fails in a complete fracture (Symes et al. 2012:355). The bending, strain, and eventually failure of a butterfly fracture is analogous to the fracture outline, angle, and surface characteristics of wet bone (L'Abbé et al. 2019). Classifying the various features of a butterfly fracture, however, will not provide more information as to the timing of that fracture. In order to do this, *biomechanical* features must be used to describe the appearance of trauma injuries, and to relate these to either wet or dry bone (L'Abbé et al. 2015, 2019). For this reason, fractography holds much promise with regard to recording tension and compression failure in both the cranium and long bones.

Trabecular bone is more compliant than cortical bone to a compressive load, a quality that is responsible for the distribution and dissipation of energy in this material and, consequentially, fracture patterns. Simon et al. (1972) noted variation in mechanical properties between trabecular and cortical bone and attributed these differences to stiffness of the material. Epiphyses demonstrate a higher degree of compressive strength and strain than the diaphyses. Thus, they are more resistant to failure under a compressive force

(Karr and Outram 2012a). This resistance to failure has been observed through the location of termination of fractures (Morlan 1984). The explanation for the ability of cancellous bone to absorb shock can either be attributed to the viscous flow of interstitial fluid or limited trabecular fractures (Simon et al. 1972 and references within; also Swanson and Freeman 1966).

The compliance of trabecular bone is most likely responsible for the termination or diversion of fractures. These actions also emphasize different mechanical properties in a single bone. Similar to other fracture characteristics, as bone degrades the compliance is lost, resulting in a higher frequency of fractures running through the epiphyses in dry bone than wet bone. As Karr and Outram (2012a) noted, however, the frequency of epiphyseal fractures is still lower than the frequency of diaphyseal fractures of bones with similar moisture content.

Discrepancies among studies investigating fracture patterns of dry and wet bone may be due in part to the classification system anthropologists have adopted from the medical or biomechanical literature (L'Abbé et al. 2019; Symes et al. 2013). Bone trauma classification terminology such as transverse, oblique, spiral, incomplete butterfly (tension wedges), transverse fractures (initiation), failure angle shifts of 45°, breakaway spurs, and further untested, but frequently cited, terminology like concentric hoop, circumferential hoop, ballistic butterfly, wastage, and hinge (Byers 2010; Fenton et al. 2012; Galloway 1999; Klepinger 2006) are not useful or accurate when describing an injury and ultimately interpreting a total body fracture pattern (L'Abbé et al. 2019). Bone is a dynamic structure, which offers tremendous variety in gross shape, size, and microstructure, and therefore, trauma is not as easily classifiable as other aspects of a skeletal report such as ancestry, sex, or stature. With this in mind, anthropologists are encouraged to adopt a biomechanical and not classificatory approach to describing injuries in skeletal remains (e.g., Christensen et al. 2018; Isa 2020; L'Abbé et al. 2019).

Case Study: Using a Taphonomic Profile and Bone Trauma Analysis to Interpret the Circumstances of Death

In the spring of 2010, two men in Pennsylvania, USA, searching for scrap metal at the bottom of a steep, wooded ravine surprisingly came upon a pair of laced-up leather work boots in the leaf litter (Figure 13.5). More shocking was the fact that protruding from these weathered boots was a pair of human leg bones (Figure 13.6) that led to a skeleton, lying face up on a bed of humus. Leaf litter concealed most of the relatively complete and dry skeleton that was haphazardly covered with clothing remnants.

For the forensic scientist field recovery, context documentation, evidence removal, and laboratory analysis are not entities unto themselves but form an integral part of any death investigation (Dirkmaat et al. 2008; Nawrocki 2009; Sorg 2019). An accurate field recovery is the first step in a comprehensive death scene and body (skeletal) analysis and aids in interpreting the circumstances of death. For this case, Pennsylvania death investigators requested that the Mercyhurst Forensic Anthropology Recovery Team at Mercyhurst University scientifically document and recover the remains and perform a laboratory analysis.

Along the bottom of the narrow ravine and in the immediate vicinity of the body, the recovery team observed large and small boulders and copious amounts of trash.

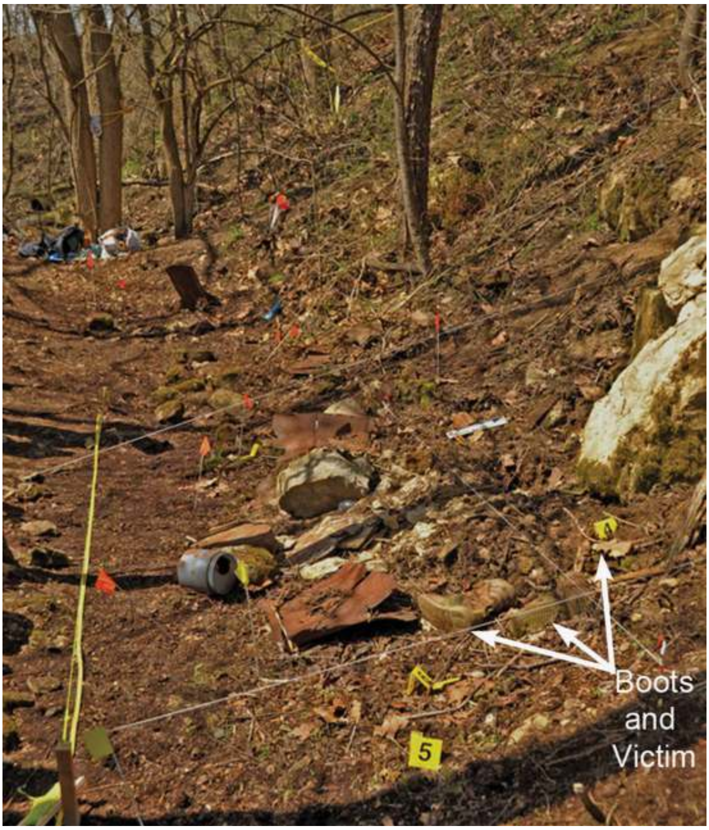

Figure 13.5 Area of scene and recovery process for case study, with mapping grid in place.

Figure 13.6 Initial finds of human remains and artifacts including boots, still in situ, case study.

Figure 13.7 Field recovery team under supervision of Dr. Dennis C. Dirkmaat, Mercyhurst University (upper right corner).

Miscellaneous trash and rocks defined the topography of this impromptu dumping site. The team began a systematic archaeological recovery, clearing years of vegetation and fallen leaves and flagging all skeletal elements and associated evidence, after which the group of trained (graduate) students established an east–west baseline through the main longitudinal axis of the site (Figure 13.7). They took measurements of artifacts and bones in association with the baseline and produced a hand-drawn map (Figure 13.8). Following the mapping process, they systematically numbered and removed skeletal elements from the surface and subsoil and placed these bones in individually numbered bags that corresponded to their map; they also screened loose soil and leaf litter for previously undetected skeletal material or artifacts.

While the crime scene was extremely complicated (cluttered) and difficult to interpret at first glance, an accurate map clarified the situation (Figure 13.8). Site maps form invaluable tools for investigations that invariably mature long after the initial scene disturbance. This case was no exception, as an encroaching boulder appeared to intrude next to the body; in fact, the map suggests that the boulder may even be on top of the body and that other large rocks in the area may also be associated with the boulder. As rocks are essentially on both sides of the body, can we assume that the boulder has damaged the skeleton? The map also illustrates the poor condition of the skull and upper body.

Other taphonomic effects include old and recent rodent dry-bone gnawing as observed on the skeleton and in this depositional setting activity from large carnivores was also probable. All bones had a red-brown tint with the exception of some lighter-colored remains, due to both subaerial weathering/sun bleaching (Figure 13.9). Numerous expended shotgun shells from more than one gauge of shotgun were also found in close association to the body (Figure 13.8). Weathering on all artifacts associated with the body was obvious and added to information as to the PMI but also further enhanced the complexity of the recovery scene. Based on the available taphonomic evidence at the scene, an author (SAS) along

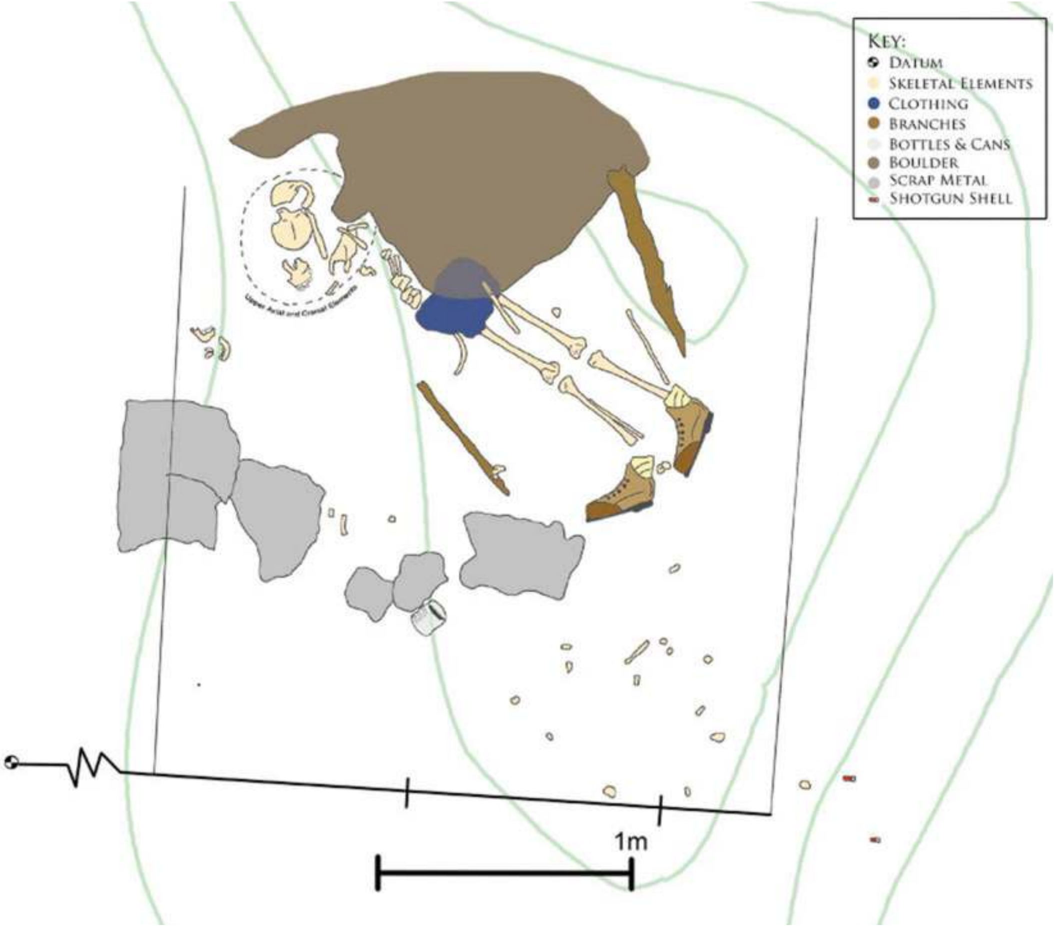

Figure 13.8 Diagram of recovery scene based on a systematic flagging and recovery process, case study.

with Dennis C. Dirkmaat of Mercyhurst University suggested a PMI greater than five years but within a rough upper limit of 10 years. Initial field estimates of PMI are always tentative, a fact about which all investigators should be routinely reminded.

As the scene was systematically dismantled, the recovery team removed skeletal remains associated with a single person, but all the bones were not recovered. After years of decomposition, deposition, and intrusion, and regardless of various archaeological methods to prevent loss, missing skeletal elements are not to be considered unusual (Chapter 9). Despite the presence of laced-up boots, many of the right foot bones were missing. Upon closer examination of the boot (Figure 13.10), the anthropologists suggested that rodents likely nested in the boot and displaced the skeletal remains. Other notable missing elements included the right parietal, right zygomatic, and right maxilla.

At the end of the day, the investigating officers provided the recovery team with more information. An 18-year-old White male had disappeared from a nearby residence, approximately 10 years prior to discovery of the skeleton. The recovery crew suddenly had a suspected identity to assign to the discolored and dry bones examined in the ravine. Initial examination of the skeleton revealed that the bones belonged to a large, adolescent male,

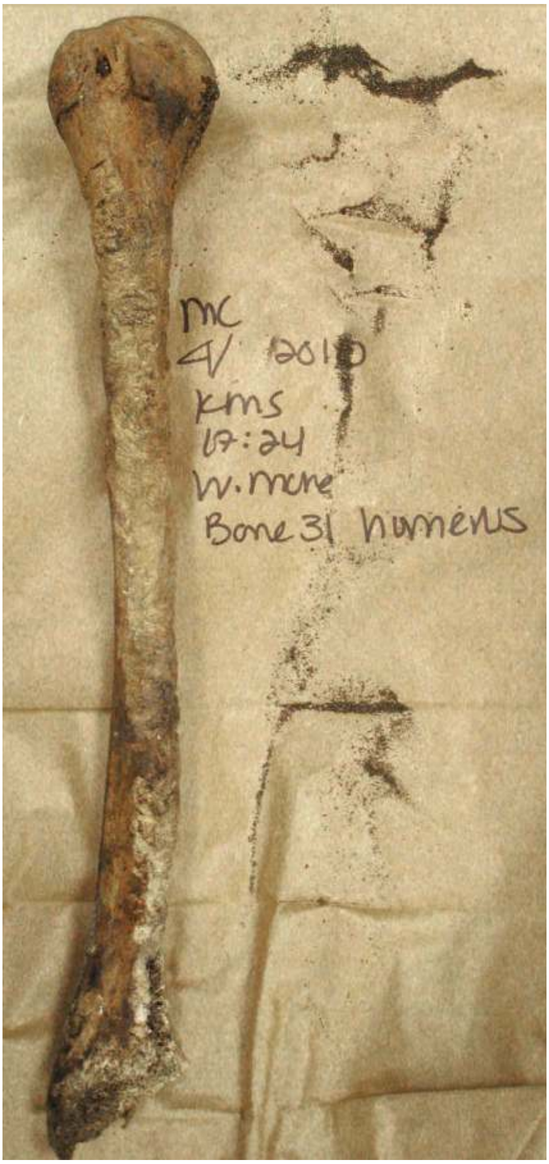

Figure 13.9 Right humerus with weathering and old and recent rodent modification, case study.

so a high probability existed that the investigation was on the right track. Unfortunately, the most important question—why a deceased 18-year-old male was lying in a ditch in the woods—had yet to be answered.

At the scene, anthropologists observed the broken bones of the cranium and associated cranial fragments in proximity to the boulder; in addition, some bones appeared to have fractured while in a postmortem state. The left humerus and mandible (Figure 13.11) had relatively old in situ crushed fractures associated with dry/degraded and weathered bone as evidenced by transverse fracture outlines and minimal evidence of compressive strains. Color change in this case was not relevant in that the dry fractures occurred long ago, and all color was the same except where the bone was exposed to the sun. Could the boulder

Figure 13.10 Close-up of the victim's right boot, indicating rodent activity that disrupted bones of the right foot.

have rolled onto the body and fractured the bones after death, or could the "expected violence" to a missing 18-year old male be the rock itself, which could have trapped the victim and caused his death? An accurate interpretation of the circumstances surrounding the victim's death was dependent on identifying the boulder/body sequence.

Cranial fragments found near the partial skull contributed to the perimortem findings and were even identified in the field (Figure 13.12). Fracture characteristics observed on these skeletal elements did not resemble dry-bone fractures like those of the mandible or left humerus but appeared bent as a consequence of wet (dynamic) bone bending in resistance to a blunt impact. The right parietal fragment (Figure 13.13) exhibited a depressed impact with plastic deformation and radiating and concentric fractures.

Radiating fractures travel away from the point of impact in adult bone, following the path of least resistance. Concentric fractures, circumferential to the point of impact, are the result of bone caving in due to blunt force (see also a reconstructed example Figure 13.14). Concentric fractures are generally secondary to radiating fractures (Berryman and Symes 1998; Smith et al. 1987; Symes et al. 2012) and are beveled inward. The external and

Figure 13.11 Mandibular remains, case study. Note the red-brown tint with lighter areas due to weathering and exposure. In situ fractures appear to have occurred to dry and weathered bone as seen with color differentiation, transverse fracture outlines, and minimal compressive strains.

Figure 13.12 Cranial fragments associated with the right parietal. Their fracture characteristics are dissimilar to dry bone fractures. Radiating and concentric fractures are visible, and the concentric fractures have beveling.

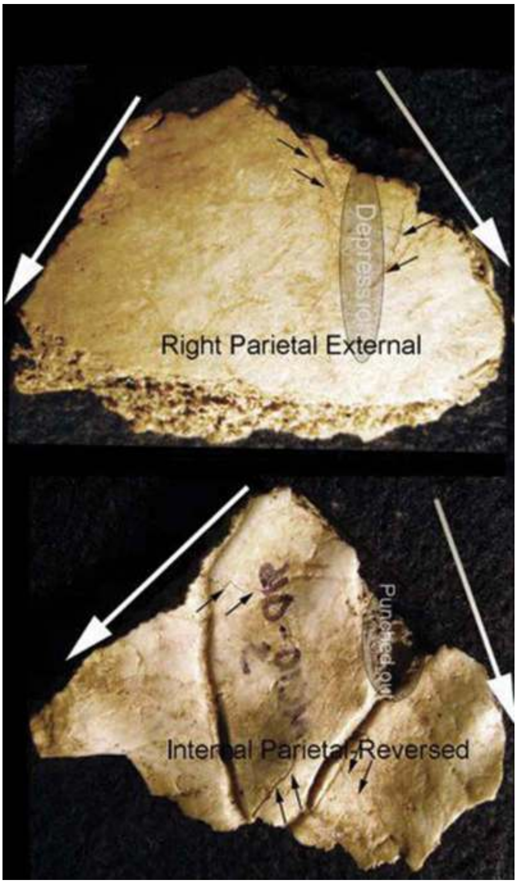

Figure 13.13 External and internal aspects of a parietal fragment, case study. The internal view has been reversed so the orientation is identical for each. Unfortunately, this fragment cannot be positioned exactly in the skull due to missing fragments of bone from the surrounding areas. While many fragments in the cranium suggest perimortem trauma, this is a classic indicator and essentially presents one of the "pie" pieces.

internal aspects of the right parietal fragment of the victim are shown in Figure 13.13. The internal view of the bone is reversed so that the orientation is identical for each view. The large white arrows denote both external and internal radiating fractures. Since radiating fractures travel away from impact sites in adults, the point of impact for this fragment is approximately where the tails of each white arrow converge (i.e., the top of each image). The small black arrows indicate minor, incomplete tension fractures surrounding an impact depression on the external surface (top image) with a resulting punched-out area on the internal surface (lower image). Finally, a beveled fracture surface is present (top image) and is magnified in Figure 13.15. The arrows pointing downward indicate initial failure in tension on the external surface as the bone bent inward. The angled arrows indicate areas of secondary failure in compression.

A depressed impact with radiating and concentric fractures likely occurred as a consequence of wet (dynamic) bone bending inward as a response to blunt force trauma. While this fragment cannot be positioned exactly in the skull due to missing bone, this fragment and others in the cranium suggest perimortem trauma. While not shown, radiating

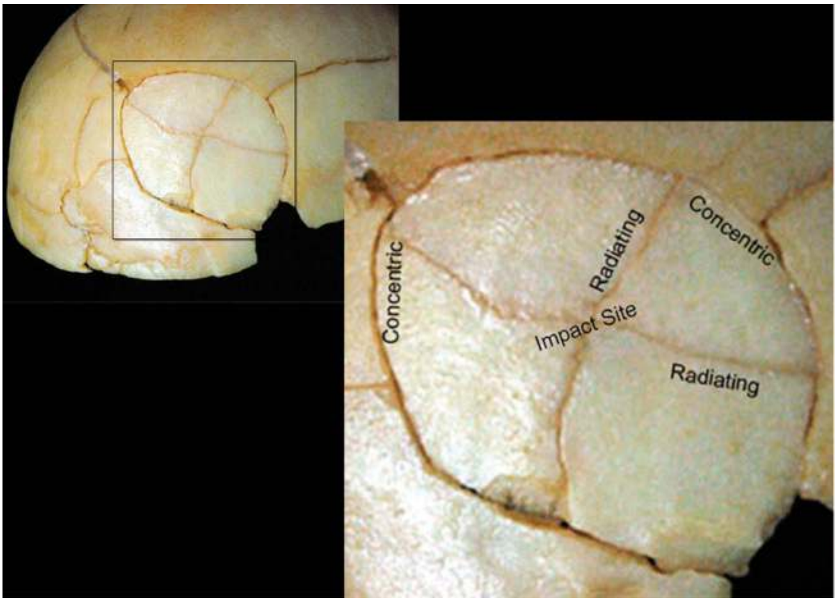

Figure 13.14 Exemplar of fresh blunt fractures (unrelated to the case study described in this chapter), illustrating wet bone failure with expressions of impact site and radiating and concentric fractures.

fractures also extended from the right external auditory meatus to the cribriform plate of the ethmoid and exemplify severe cranial trauma in fresh bone.

With both perimortem and postmortem trauma diagnosed on the skull, the bones with rodent gnawing found under the boulder were essential for interpreting the order of events and for demonstrating the necessity of understanding the full suite of taphonomic processes (Figure 13.16). Rodents frequently gnaw on dry bones devoid of soft tissue,

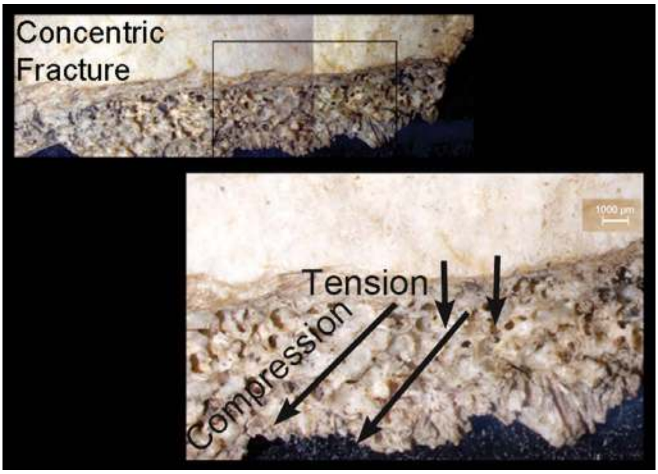

Figure 13.15 Close-up of the bevel of the parietal fragment shown in Figure 13.13, case study. The arrows pointing down indicate tension that occurred initially to the external surface, as the bone bends inward at the point of impact. The angled arrows are indicative of areas of compression failure on the bone.

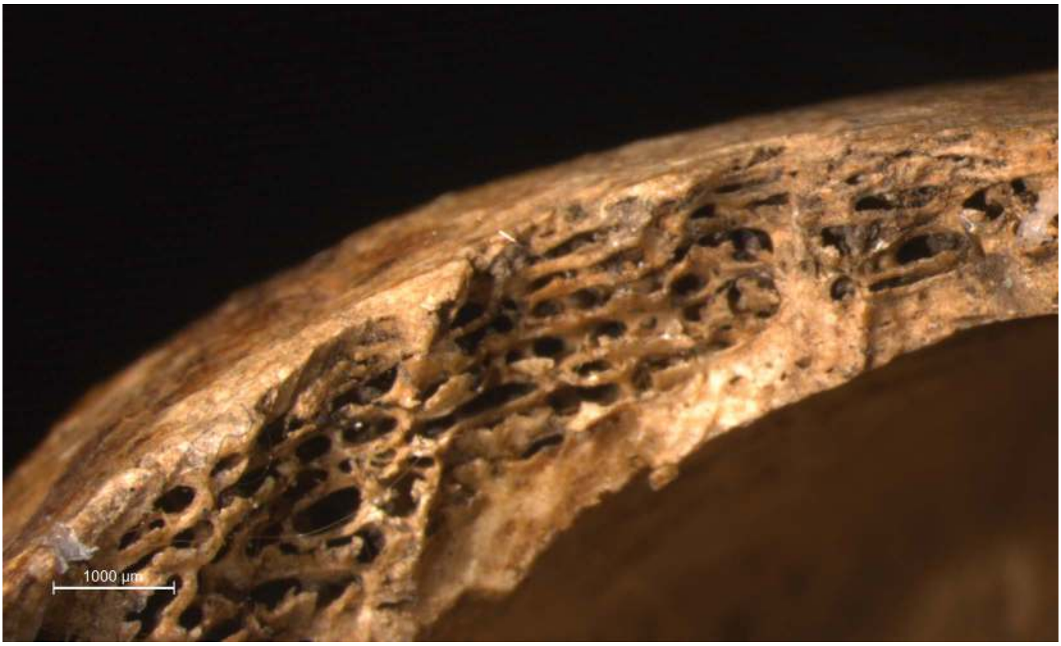

Figure 13.16 Residual rodent modification on the skull. The area may have been a perimortem fracture site, but now the area is obscured as the result of postmortem influence.

which is generally months or years after death (Klippel and Synstelien 2007; Chapter 9). For rodents to reach specific skull and arm bones, the elements had to be both exposed and dry. Therefore, the boulder had fallen into the current position months or more likely years after the body had been deposited and decomposed.

Without a thorough analysis and knowledge of the scene and bone trauma, one may be quick to assume that all defects were due to the boulder. However, the fracture patterns suggested that the boulder fell on top of the remains following their deposition and decomposition. The location of the rodent-gnawed bones corroborates this scenario. Without a forensic anthropologist on scene, the context of the rodent-gnawed bones would have been lost, and, furthermore, the ability to interpret the order of events fully would have been impossible (Chapters 20 and 21). The case study illustrates the complexities of a forensic anthropological analysis that involves dry- and wet-bone fractures as well as taphonomic modifications. In the current example, it was crucial to decipher the differences between wet- and dry-bone fractures as well as to interpret the order of events. Ensuing investigations led to matching the bones to the missing 18-year-old. The eventual questioning of a likely suspect produced an initial confession describing an accidental hunting death due to a shotgun wound. Prior knowledge of blunt force as opposed to a gunshot wound to the head eventually enabled investigators to get a full confession from the suspect, describing a lethal beating.

Conclusions

How do forensic archaeologists and anthropologists interpret the circumstances surrounding death, and can they supply information as to the cause and manner of death? How does one decide whether a body had been dumped or whether a person died on the scene? What are the repercussions for supplying an incorrect analysis to law enforcement or a court of law? These questions form an intellectual foundation for research in both taphonomy and bone trauma analysis. In a criminal trial, the role of the forensic anthropologist has always remained unclear. Unlike forensic pathologists and coroners who are paid to make decisions on the cause and manner of death, a forensic anthropologist is not pressured to do so. Therefore, in a court, comments and evidence from a forensic anthropologist are purely voluntary. As such, the implications of their statements are less often reviewed, discussed, or debated in the literature, yet all testimony—mandatory or voluntary—has implications for both the accused and for the outcome of a court case, particularly in a homicide. Despite continual pontifications among forensic anthropologists on the *Daubert* ruling and the associated rules for expert testimony, less attention is given to the implications of this testimony, either for the anthropologist or for the trial. Any skeletal analysis may adhere to a series of guidelines and may be acceptable in court; however, the interpretation of the outcome of the analysis, particularly with regard to bone trauma analysis, is far more important.

This chapter describes the biomechanical properties and fracture morphology of wet and dry bone. A connection to the theoretical foundation (biomechanical principles) is necessary in order to make meaningful, or valid, observations in trauma analysis (Houle et al. 2011; L'Abbé et al. 2019). As scientists, we need to ensure that "inferences about [our variables] reflect the underlying reality that we intend to represent" (Houle et al. 2011:4). In other words, our work has to be valid, and in trauma analysis, biomechanics are the basis of bone failure analysis. The fracture morphology of fresh or dry long bones under a slow-loaded or rapid-loaded force is based on the biomechanical properties of the impactor and the material (nonhomogeneous, viscoelastic, anisotropic, and brittle).

Despite the literature on fracture classification, anthropologists need an awareness of bone reaction to force. Fracture patterns or angles of the failure are important to describe and for ease of recognition; however, the features of strain modes appear to be the best indicators for fracture interpretation (Christensen et al. 2018; L'Abbé et al. 2015, 2019). Anthropologists need to grasp the biomechanical concepts that are reflective in the fracture characteristics and acknowledge the properties in anthropological reports and in testimony. In other words, anthropologists need to return to the basic interpretation of bone fractures (L'Abbé et al. 2015, 2019; Symes et al. 2012, 2013).

The theoretical issue surrounding wet- and dry-bone fractures can be split into two categories: description and interpretation.

Description

Overall, the literature regarding fracture characteristics is sparse, and few studies have tested samples with a PMI greater than five months. Although general trends can be seen in the results, so can inconsistencies with diagnostic features for dry bone observed in wet-bone samples and vice versa. Varying results are most likely the consequence of differing environments and microenvironments that ultimately affect the moisture in the skeletal sample. As noted earlier, the moisture content is the main variable that directly influences a bone's response to force. Moisture loss is a gradual and variable process such that a discrete time period may be impossible to provide. Furthermore, a descriptive approach is recommended until research that evaluates the probability of a PMI based on the observed fracture characteristics is completed. Above all, knowledge of taphonomic influences that affected the remains is necessary in order to develop an accurate interpretation of any skeletal trauma (Dirkmaat et al. 2008; Dirkmaat and Adovasio 1997).

Interpretation

Anthropologists attempt to categorize a continuous variable of unspecified duration into two arbitrary divisions: perimortem and postmortem. Division of a gradual and ambiguous process such as decomposition into two events is discordant with the available material (decomposed or skeletonized remains) (Shattuck 2010; Wheatley 2008; Wieberg and Wescott 2008). Similarly, it is ineffective when attempting to describe a fracture. Forensic pathologists use the terminology to signify a temporal period rather than the physical condition of bone. Anthropologists need to refer to the bony response as indicative of either wet or dry bone, as one observes the state that the bone is in when it is exposed to forces that caused a fracture (Kemp 2016; L'Abbé et al. 2019; Symes et al. 2012).

In summary, the interpretation of traumatic injury on bone is a critical component of forensic anthropological case reports. Unlike biological profiles that focus on victim identification, a trauma report is based on the use of soft- or hard-tissue injuries to provide an opinion on the type of trauma inflicted and perhaps the mechanism from which these injuries occurred. In a court of law, the interpretation of either the cause and/or manner of death from skeletal elements has tremendous implications. In any reconstruction of traumatic injury to bone, descriptions of "wet" and "dry" need to be used to clarify bone condition. Further interpretations as to the timing of the injury, perimortem or postmortem, can be ascertained only when the context in which the remains were found is known, and even then, interpretation has been shown to be difficult (Dirkmaat et al. 2008; Dirkmaat and Adovasio 1997; L'Abbé et al. 2019; Sorg 2019).

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References

Berryman, H. E., and S. A. Symes (1998) Recognizing gunshot and blunt cranial trauma through fracture interpretation. In *Forensic Osteology: Advances in the Identification of Human Remains* (2nd ed.) ed. by K. J. Reichs, pp. 333–352. Charles C Thomas, Springfield, IL.

Berryman, H. E., S. A. Symes, O. C. Smith, and S. J. Moore (1991) Bone fracture II: Gross examination of fractures. *Proceedings of the 43rd Annual Meeting of the American Academy of Forensic Sciences* p. 150, Anaheim, CA.

Biddick, K. A., and J. Tomenchuk (1975) Quantifying continuous lesions and fractures on long bones. *Journal of Field Archaeology* 2(3):239–249.

Bonnichsen, R. (1979) *Pleistocene Bone Technology in the Beringian Refugium*. Archaeological Survey of Canada. Paper 89:1–280.

Breytenbach, B. (2008) *A Veil of Footsteps: Memoir of a Nomadic Fictional Character.* NB Publishers, Cape Town, South Africa.

Byers, S. N. (2010) *Introduction to Forensic Anthropology* (4th ed.). Pearson Custom Anthropology, Upper Saddle River, NJ.

Calce, S. E., and T. L. Rogers (2007) Taphonomic changes to blunt force trauma: A preliminary study. *Journal of Forensic Sciences* 52(3):519–527.

Cappella, A., A. Amadasi, E. Castolidi, D. Mazzarelli, D. Gaudio, and C. Cattaneo (2014) The difficult task of assessing perimortem and postmortem fractures on the skeleton: A blind text of 210 fractures of known origin. *Journal of Forensic Sciences* 59(6):1598–1601.

Cattaneo, C., and A. Capella (2017) Distinguishing between perimortem and postmortem trauma on bone. In *Taphonomy of Human Remains: Analysis of the Dead and the Depositional Environment* ed. by E. M. J. Schotsmans, N. Márquez-Grant, and S. L. Forbes, pp. 352–368. Wiley, West Sussex, UK.

Cattaneo, C., A. Cappella, and E. Cunha (2017) Post mortem anthropology and trauma analysis. In *P5 Medicine and Justice* ed. by S. Ferrara, pp. 166–179. Springer, Cham, Switzerland.

Christensen, A. M., J. T. Hefner, M. A. Smith, J. B. Webb, M. C. Bottrell, and T. W. Fenton (2018) Forensic fractography of bone: A new approach to skeletal trauma analysis. *Forensic Anthropology* 1(1):32–51.

Cunha, E., and J. E. Pinheiro (2009) Antemortem trauma. In *Handbook of Forensic Anthropology and Archaeology* ed. by S. Blau and D. H. Ubelaker, pp. 246–262. Left Coast Press, Walnut Creek, CA.

Currey, J. D. (2002) *Bones: Structure and Mechanics* (2nd ed.). Princeton University Press, Princeton, NJ.

de Gruchy, S., and T. L. Rogers (2002) Identifying chop marks on cremated bone: A preliminary study. *Journal of Forensic Sciences* 47(5):933–936.

Dirkmaat, D. C., and J. M. Adovasio (1997) The role of archaeology in the recovery and interpretation of human remains from an outdoor forensic setting. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 39–64. CRC Press, Boca Raton, FL.

Dirkmaat, D. C., L. L. Cabo, S. D. Ousley, and S. A. Symes (2008) New perspectives in forensic anthropology. *Yearbook of Physical Anthropology* 51:33–52.

Einhorn, T. A. (2005) The science of fracture healing. *Journal of Orthopedic Trauma* 19:S4–S6.

Emrith, T. S., C. G. Mole, and M. Heyns (2020) Interpreting impact direction: Applying fractography to the analysis of butterfly fractures produced by blunt force trauma. *Australian Journal of Forensic Sciences* 21:1–16. DOI: 10.1080/00450618.2020.1781252.

Fenton, T. W., A. E. Kendell, T. S. Deland, and R. C. Haut (2012) Determination of impact direction based on fracture patterns in human long bones. *Proceedings of the American Academy of Forensic Sciences* 18:398.

Frankel, V. H., and M. Nordin (2001) Biomechanics of bone. In *Basic Biomechanics of the Musculoskeletal System* (3rd ed.) ed. by. V. H. Frankel and M. Nordin, pp. 26–59. Lippincott Williams and Wilkins, Philadelphia.

Galloway, A. (ed.) (1999) *Broken Bones: Anthropological Analysis of Blunt Force Trauma*. Charles C Thomas, Springfield, IL.

Green, A. E., and J. J. Schultz (2017) An examination of the transition of fracture characteristics in long bones from fresh to dry in Central Florida: Evaluating the timing of injury. *Journal of Forensic Sciences* 62(2):282–291.

Hansen, U., P. Zioupos, R. Simpson, J. D. Currey, and D. Hynd (2008) The effect of strain rate on the mechanical property of human cortical bone. *Journal of Biomechanical Engineering* 130(1):011011. DOI: 10.1115/1.2838032.

Harkess, J. W., and W. C. Ramsey (1996) Principles of fractures and dislocations. In *Rockwood and Green's Fractures in Adults* (4th ed.) ed. by C. A. Rockwood, D. P. Green, R. W. Bucholz, and J. D. Heckman, pp. 3–21. Lippincott-Raven, Philadelphia.

Hentschel, K. C. (2014) *Postmortem Fracture Surface Topography: An Investigation into Differentiating Perimortem and Postmortem on bone Blunt Force Trauma fractures*. M.A. Thesis, Texas State University, Austin, TX.

Hildebrand, M., and G. Goslow, Jr. (2001) *Analysis of Vertebrate Structure* (5th ed.). Wiley, New York.

Hill, A. P. (1980) Early postmortem damage to the remains of some contemporary East African mammals. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 131–155. University of Chicago Press, Chicago.

Honeycutt, K. K. (2012) *Fracture Patterns and Taphonomic Processes in a Mass Grave Environment: A Quantitative Analysis*. M.A. Thesis, North Carolina State University, Raleigh, NC.

Houle, D., C. Pélabon, G. P. Wagner, and T. F. Hansen (2011) Measurement and meaning in biology. *Quarterly Review of Biology* 86(1):3–32.

Isa, M. I. (2020). *Experimental Investigations of Blunt Force Trauma in the Human Skeleton*. Ph.D. Dissertation, Michigan State University, Ann Arbor, MI.

Janjua, M. A., and T. L. Rogers (2008) Bone weathering patterns of metatarsal verses femur and the postmortem interval in Southern Ontario. *Forensic Science International* 178(1):16–23.

Johnson, E. (1985) Current developments in bone technology. In *Advances in Archaeological Method and Theory* (vol. 8) ed. by M. B. Schiffer, pp. 157–235. Academic Press, Orlando, FL.

Karr, L. P., and A. K. Outram (2012a) Actualistic research into dynamic impact and its implications for understanding differential bone fragmentation and survivorship. *Journal of Archaeological Science* 39(11):3443–3449.

Karr, L. P., and A. K. Outram (2012b) Tracking changes in bone fracture morphology over time: Environment, taphonomy, and the archaeological record. *Journal of Archaeological Science* 39(2):555–559.

Keller, T. S., Z. Mao, and D. M. Spengler (1990) Young's Modulus bending strength and tissue physical properties of human compact bone. *Journal of Orthopaedic Research* 8(4):592–603.

Kemp, W.L (2016) Postmortem changes and its effect on evaluation of fractures. *Academic Forensic Pathology* 6(1): 28–44

Klepinger, L. L. (2006) Fundamentals of forensic anthropology. In *Foundation of Human Biology* ed. by M. Cartmill and K. Brown, pp. 101–117. Wiley, Hoboken, NJ.

Klippel, W. E., and J. A. Synstelien (2007) Rodents as taphonomic agents: Bone gnawing by brown rats and gray squirrels. *Journal of Forensic Sciences* 52(4):765–773.

Komar, D., and J. E. Buikstra (2008) *Forensic Anthropology: Contemporary Theory and Practice*. Oxford University Press, New York.

L'Abbé, E. N., S. A. Symes, J. T. Pokines, L. L. Cabo, K. E. Stull, S. Kuo, D. E. Raymond, P. S. Randolph-Quinney, and L. R. Berger (2015) Evidence of fatal skeletal injuries on Malapa Hominins 1 and 2. *Scientific Reports* 5(1):151120. DOI: 10.1038/srep15120.

L'Abbé, E. N., S. A. Symes, D. E. Raymond, and D. Ubelaker (2019) The Rorschach Butterfly, understanding bone biomechanics prior to using nomenclature in bone trauma interpretations. *Forensic Science International* 299(1):187–194.

LaCroix, M. (2013) *A Study of the Impact of Weathering upon the Minimal Force Required to Fracture Bone*. M.S. Thesis, Boston University School of Medicine, Boston.

Lee, P., T. B. Hunter, and M. Taljanovic (2004) Musculoskeletal colloquialisms: How did we come up with these names? *Radiographics* 24(4):1009–1027.

Low, J., and A. Reed (1996) *Basic Biomechanics Explained*. Reed Educational and Professional Publishing, Oxford.

Matrille, L., and S. A. Symes (2019) Interpretation of long bones ballistic trauma. *Forensic Science International* 302:109890. DOI: 10.1016/j.forsciint.2019.109890.

Morlan, R. E. (1984) Toward the definition of criteria for the recognition of artificial bone alterations. *Quaternary Research* 22(2):160–171.

Nawrocki, S. P. (2009) Forensic taphonomy. In *Handbook of Forensic Anthropology and Archaeology* ed. by S. Blau and D. H. Ubelaker, pp. 284–295. Left Coast Press, Walnut Creek, CA.

Nawrocki, S. P., J. E. Pless, D. A. Hawley, and S. A. Wagner (1997) Fluvial transport of human crania. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 529–548. CRC Press, Boca Raton, FL.

Özkaya, N., and M. Nordin (1999) *Fundamentals of Biomechanics: Equilibrium, Motion, and Deformation* (2nd ed.). Springer, New York.

Pechníková, M., D. Porta, and C. Cattaneo (2011) Distinguishing between perimortem and postmortem fractures: Are osteons of any help? *International Journal of Legal Medicine* 125(4):591–595.

Pierson, O. M., and D. E. Lieberman (2004) The aging of Wolff's law: Ontogeny and responses to mechanical loading in cortical bone. *American Journal of Physical Anthropology* 125(S39):63–99.

Reilly, D. T., and A. H. Burstein (1974) The mechanical properties of cortical bone. *Journal of Bone and Joint Surgery* 56A:1001–1022.

Ribeiro, P., X. Jordana, S. Scheirs, M. Ortega-Sánchez, A. Rodriguez-Baeza, H. McGlynn, and I. Galtés (2020) Distinction between perimortem and postmortem fractures in human cranial bone. *International Journal of Legal Medicine* 134(5):1765–1774.

Sauer, N. (1998) The timing of injuries and the manner of death: Distinguishing among antemortem, perimortem, and postmortem trauma. In *Forensic Osteology: Advances in the Identification of Human Remains* (2nd ed.) ed. by K. J. Reichs, pp. 321–332. Charles C Thomas, Springfield, IL.

Scheirs, S., M. Cos, H. McGlynn, M. Ortega-Sánchez, A. Malgosa, and I. Galtés (2020) Visualization and documentation of perimortem traits in long bone fractures using computed tomography. *Forensic Science, Medicine and Pathology* 16(2):281–286.

Scheirs, S., B. Hevink, M. Ortega-Sánchez, X. Jordana, H. McGlynn, A. Rodriguez-Baeza, A. Malgosa, and I. Galtés (2019) Intra vitam trauma pattern: Changing the paradigm of forensic anthropology? *International Journal of Legal Medicine* 133(2):661–668.

Scheirs, S., W. Lagenhorst, A. Malgosa, M. Ortega-Sánchez, H. McGlynn, C. Santos, X. Jordana, A. Rodriguez-Baeza, and I. Galtés (2018) Perimortem fracture patterns in ribs by blunt force trauma. *International Journal of Legal Medicine* 132(4):1205–1213.

Scheirs, S., A. Malgosa, D. Sanchez-Molina, M. Ortega-Sánchez, J. Velázquez-Ameijide, C. Arregui-Dalmases, J. Medallo-Muñiz and I. Galtés (2017) New insights in the analysis of blunt force trauma in human bones. Preliminary results. *International Journal of Legal Medicine* 131(3):867–875.

Shattuck, R. E. (2010) *Perimortem Fracture Patterns in South-Central Texas: A Preliminary Investigation into the Perimortem Interval.* M.A. Thesis, University of Texas, San Marcos, TX.

Simon, S. R., E. L. Radin, I. L. Paul, and R. M. Rose (1972) The response of joints to impact loading—II. In vivo behavior of subchondral bone. *Journal of Biomechanics* 5(3):267–272.

Smith, O. C., H. E. Berryman, and C. H. Lahren (1987) Cranial fracture patterns and estimate of direction of low velocity gunshot wounds. *Journal of Forensic Sciences* 32(5):1416–1421.

Sorg, M. H. (2019) Differentiating trauma from taphonomic alterations. *Forensic Science International* 302(S):109893. DOI: 10.1016/j.forsciint.2019.109893.

Swanson, S. A. V., and M. A. R. Freeman (1966) Is bone hydraulically strengthened? *Medical and Biological Engineering* 4(5):433–438.

Symes, S. A., E. N. L'Abbé, E. N. Chapman, I. Wolff, and D. C. Dirkmaat (2012) Interpreting traumatic injury from bone in medicolegal investigations. In *A Companion to Forensic Anthropology* ed. by D. C. Dirkmaat, pp. 340–389. Wiley-Blackwell, London.

Symes, S. A., E. N. L'Abbé, K. E. Stull, I. Wolff, and D. E. Raymond (2013) A return to the basic principles of biomechanics to interpret blunt force trauma in long bones. *Proceedings of the American Academy of Forensic Sciences* 19:409–410.

Symes, S. A., O. C. Smith, H. E. Berryman, C. E. Peters, L. A. Rockhold, S. J. Haun, J. T. Francisco, and T. P. Sutton (1996) *Bones: Bullets, Burns, Bludgeons, Blunderers, and Why.* Workshop conducted at the *48th Annual Meeting of the American Academy of Forensic Sciences*, Nashville, TN.

Tencer, A. F. (2006) Biomechanics of fixation and fractures. In *Rockwood and Green's Fractures in Adults* (6th ed.) ed. by C. A. Rockwood, D. P. Green, R. W. Bucholz, and J. D. Heckman, pp. 3–42. Lippincott-Raven, Philadelphia.

Thornton, J. I., and P. J. Cashman (1986) Glass fracture mechanism—A rethinking. *Journal of Forensic Sciences* 31(3):818–824.

Ubelaker, D. H., and B. J. Adams (1995) Differentiation of perimortem and postmortem trauma using taphonomic indicators. *Journal of Forensic Sciences* 40(3):509–512.

Villa, P., and E. Mahieu (1992) Breakage patterns of human long bones. *Journal of Human Evolution* 21(1):27–48.

Wescott, D. J. (2019) Postmortem change in bone biomechanical properties: Loss of plasticity. *Forensic Science International* 300:164–169.

Wheatley, B. P. (2008) Perimortem or postmortem bone fractures? An experimental study of fracture patterns in deer femora. *Journal of Forensic Sciences* 53(1):69–72.

Wieberg, D. A. M., and D. J. Wescott (2008) Estimating the time of long bone fractures: Correlation between postmortem interval, bone moisture content, and blunt force trauma fracture characteristics. *Journal of Forensic Sciences* 53(5):1028–1034.

Zioupos, P., U. Hansen, and J. D. Currey (2008) Microcracking damage and the fracture process in relation to strain rate in human cortical bone tensile failure. *Journal of Biomechanics* 41(14):2932–2939.

Thermal Alteration to Bone

14

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Contents

> Together, hand in hand, with that stick of matches, with our necklace, we shall liberate this country.
>
> **—Mrs. Winnie Madikizela-Mandela**
> *1986 speech*

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Introduction

Few taphonomic alterations to bone are as destructive, rapid, predictable, and common in forensic settings as combustion of fleshed bodies or isolated remains (Bass 1984; Fairgrieve 2008; Heglar 1984; Mayne Correia 1997; Mincer et al. 1990; Ubelaker 2009), especially when commercial cremation and subsequent processing are involved (Warren and Schultz 2002). Thermal destruction of bone usually results from continued combustion of an intact body and is associated with an endless array of possibilities, such as house fires, fatal car crashes, airplane accidents, explosions, or "necklacing" (a type of homicide) (Symes et al. 2012, 2015). Thermal destruction also occurs when a perpetrator deliberately destroys a body or other evidence of criminal activity (Baker 2004; Herrmann and Bennett 1999; Owsley 1993; Owsley et al. 1993; Pope and Smith 2004; Symes et al. 2015), so the effects of fire on perimortem and postmortem trauma must be examined and considered. Boiling and cooking are also destructive to bone, albeit less common in a forensic setting than combustion of intact bodies, unless one includes the effects of deliberate maceration of skeletal remains (Fenton et al. 2003; Rennick et al. 2005; Chapter 15, this volume).

Standard commercial (funerary) cremation practices also pose a challenge to forensic anthropologists. For example, an expert may be asked whether a set of cremains found outdoors represents the scattering of funeral ashes or an attempt to conceal a crime (Baker 2004). More often, forensic anthropologists are requested to determine whether a funeral home presented the correct cremains to the next of kin and not those of another person or an inorganic substance. The most prominent incident of "false cremains" was at the Tri-State Crematory in Georgia with several other incidents also occurring in the USA. The gross negligence associated with false cremains was attributed to a lack of formal government inspections on the funerary institutions (Brooks et al. 2006; Kennedy 1996; Murray and Rose 1993; Rosen 2004; Ubelaker 2009; Warren and Schultz 2002). While standard osseous analytical techniques and chemical testing are often necessary to answer questions regarding who or what is contained in the purported cremains (Schultz et al. 2008), the increase in cremations for both human and nonhuman remains and the increase in fraudulent claims surrounding cremated bodies require that forensic anthropologists also understand the processes and taphonomic effects of commercial cremations. The aim of this chapter is to describe thermal alteration to intact bodies and skeletal elements within a combustion spectrum that includes common forensic scenarios (house fires, criminal activity, motor vehicle accidents, etc.), cooking (maceration, consumption, etc.), and formal cremations (cremains, etc.). Burned bone fracture characteristics are discussed as a possible means to evaluate the condition of remains prior to burning, such as fleshed/wet and dry and to differentiate burned bone fractures from prior perimortem injury—sharp, blunt, and ballistic/projectile trauma.

Fire Modification of Bodies and Bones

Fire modification begins with soft tissue, as bones are usually positioned at the center of several layers of tissue: muscle, connective, adipose (subcutaneous fat), and epithelium (skin) in addition to clothing (Bohnert et al. 1998; Pope 2007; Symes et al. 2015; Thompson 2004, 2005). Differences in soft tissues within the body that protect and insulate deeper layers (including bone) correspond to differential effects of burning, which vary depending on body region and individual skeletal element (Table 14.1). Anyone with practical experience

Table 14.1 Qualitative Burn Traits and Their Associated Definitions for Assessing Burned Remains

Trait	Definitions (Keough et al. 2012, 2015; Symes et al. 2015)
	General
Normal Burn Pattern	Appearance of thermally altered bone is consistent with normal tissue shielding, color change, and fracture biomechanics (Figure 14.5a,b).
Joint Shielding	Area of articulation between two bones is unburned as the joint was articulated during the burn event and the unburned area was protected from fire (Figure 14.7).
Greasy Surface	Texture of the unaltered bone is greasy (wet) (Figure 14.10).
Decomposition Staining	Discoloration (often brown) on bone attributed to staining from the decomposition process and surrounding environment (soil) (Figures 14.11 and 14.17).
Heat-Altered Border	White to brown in color with a variable width. Found between a heat line (which may be white or brown) and carbonized bone. Discoloration of bone is from exposure to heat and/or flame but not to the extent that the bone has become carbonized (Figure 14.8).
White Heat Line	Transition between heat-altered and unaltered bone. Adjacent to the heat-altered border. White heat lines (Figures 14.8 and 14.9) are noted in fleshed remains (Gough et al. 2021; Symes et al. 2015), whereas brown heat lines (Figures 14.11–14.13) are found in dry remains.
	Heat-Altered Cracking
Predictable	Distinct fracture lines that run parallel to the heat border. These fractures are found at the transition area between the heat border and the charred area. Dehydration from heat exposure causes bone to shrink and crack within the border (Figures 14.8 and 14.9).
Minimal	Non-distinct, random fracture lines (non-parallel) within the heat altered border. These fractures are not associated with the mechanisms that create predictable fractures but can be attributed to direct exposure to fire (Figure 14.12).
	Color
Carbonized	Carbonized (charred) bone that is black in color and indicates that the skeletal material had been in direct contact with the fire (Figures 14.8 and 14.9).
Calcined	White to gray in color with no organic material present (Figures 14.2, 14.8, and 14.9).
	Fractures
Curved Transverse	The cracking of fleshed/wet bone from direct heat. Curved (thumbnail) fractures form along the grain of the bone. Most commonly observed with fleshed/wet remains but have been observed in skeletonized remains (Gonçalves et al. 2011) (Figures 14.14 and 14.15).
Coning	Most often observed in long bones. Curved transverse (thumbnail) fractures break off from the bone and leave a smooth, beveled appearance to the long bone shaft (Figure 14.16).
Longitudinal	The shrinking and warping of bone from direct heat causes the formation of longitudinal and transverse cracks along the grain of the bone and parallel to the Haversian canals. As noted with curved transverse and coning, the fractures can also be spiral or helical shaped (Figures 14.2 and 14.14).
Transverse	Associated with longitudinal fractures. These fractures transect the Haversian canal and are a result of bone shrinking and tension failure. A transverse fracture should not be confused with a sharp force injury (Figures 14.2 and 14.16).
Step	Most often observed in long bones. The longitudinal and transverse fractures break off the diaphyseal shaft and leave a stepped-like appearance (Figure 14.18).
Patina	A fine mesh of superficial patterned cracks on the surface of the bone, is indicative of a broad area of bone receiving uniform heat (Figure 14.16).
Delamination	The splitting of the outer and inner tables of bone, mostly observed in the skull and should not be confused with blunt force injury (and vice versa) (Figure 14.8).

in cooking meat on a fire knows that exposure to high temperatures can carbonize (char) the outside of a piece of meat, including skin, connective tissues, and superficial muscles tissues, while protecting the inner tissues from cooking, scorching, and further fire modification (Roberts et al. 2002). Using knowledge of soft tissue structures and thermal alteration, forensic anthropologists are able to reconstruct and assess expected patterns of fire modification to bone.

Heat-induced changes to bones and teeth may be confused with common taphonomic agents mimicking thermal alteration such as contact with soil or manganese oxide (López-González et al. 2006; Shahack-Gross et al. 1997; Chapters 5 and 12), sun bleaching (Chapters 11 and 12), or fungal activity (Piepenbrink 1986). Heat-induced warping can also be confused with taphonomic processes such as sediment pressure (Buikstra and Ubelaker 1994) and even by pathological conditions such as Paget's disease, osteomalacia, rickets, and congenital syphilis (Mays 2008; Ortner 2008). In turn, fractures can be caused by several agents such as subaerial weathering, root growth, or animal activity (Behrensmeyer 1978; Ubelaker 1997; Chapters 5, 9, 11, and 19). For example, curved transverse fractures (Table 14.1) are exclusively caused by exposure to high temperatures of long duration, such as a car fire, house fire, or a cremation (Symes et al. 2015, Gonçalves et al. 2011). If these fractures are absent, and context is not known, then one cannot exclude the possibility of a thermal event.

Four research areas into fire modification that are discussed in this chapter and are most pertinent to forensic anthropologists include: (1) visual classification and identification of bone from color changes due to carbonization and calcination, (2) experimental research into whole body burn patterns, (3) trauma interpretation, and (4) historical and modern cremations.

Color Changes

During combustion, and with increasing damage to soft tissue and bone, a full spectrum of color changes are observed and range from natural beige, to carbonized (black), gray with blue tints, gray, and then to white, with the last color representing full calcination (Mayne Correia 1997; Mayne Correia and Beattie 2002; Symes et al. 2015). In terms of color, bone reacts somewhat predictably to heat increments. Bone gradually displays darker colors (brown, gray, black) up to approximately 500°C and then, as calcination commences, it will induce lighter colors (gray, blue, white) to the bone (Bonucci and Graziani 1975; Etxeberria 1994; Shipman et al. 1984; Walker et al. 2008). As a result, differential heat intensity affecting a skeleton is interpretable from the differential color patterns. The pattern and distribution of color on a single bone or multiple bones, however, varies based on circumstances such as perimortem injury (see case studies, below), previous *decomposition staining* (discoloration [often brown] on bone attributed to staining from the decomposition process and surrounding environment), skeletonization, as well as variation in temperature and duration of burning.

Burned bone undergoes various color changes that camouflage it with surrounding burned objects, a situation that can impede complete recovery of fragmented remains (Devlin and Herrmann 2008; Ubelaker et al. 1995; Walker and Miller 2005; Walker et al. 2008; Chapter 17). In car accidents, airplane crashes, and other burning events involving people and inorganic remains, burned bone often has substances melted onto it. These may derive from artificial fiber clothing, shoe portions, or the interior objects of automobiles,

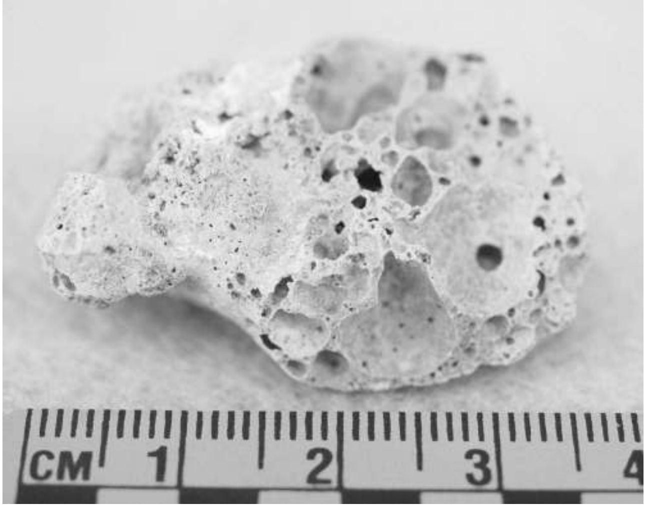

Figure 14.1 Melted plastic that provides the illusion of cancellous bone. Note the irregular structure to the porous spaces, formed by bubbling gases.

aircraft, or buildings, and the substances involved may include nylon, polyester, or a variety of plastic types. Each of these melts as it burns and can create a mass of partially carbonized residue that is fluid and can conform over surfaces, including bone. These melted artificial substances can also superficially mimic the structure of bone (Figure 14.1). This is especially true of plastic materials that emit gases when combusting, which bubble through the molten plastic or other material and leave behind air spaces when the carbonized substance cools.

Teeth experience color changes that do not exactly parallel those of bones. Even though tooth enamel and dentine have a much lower organic content than bones, the same gradual breakdown of the organic molecules into carbon followed by a loss of carbon occurs (see below) (Beach et al. 2008; Schmidt 2008). However, unlike cortical bone, heat-induced warping is less visible (Oliveira-Santos et al. 2017; Sandholzer et al. 2013, 2014). Beach et al. (2008) heated dental specimens in a muffle furnace to temperatures ranging from 400°C to 1000°C for 30 or 60 min in their experimental study. During intermediate heating stages, the enamel became translucent, and the teeth took on a red-brown color as the dentin increased in visibility. With additional exposure temperature/duration, enamel turned a dark, metallic gray and retained a glossy texture. Crowns became light gray and were very friable, sometimes disintegrating into multiple fragments. The color of tooth roots, which are within the alveolar bone and more protected than crowns, advanced from the original beige/yellow of unaltered dentin to carbonized, brown/olive, gray, and then calcined with some loss of structural integrity. These thermal changes were generally more consistently observable in roots, as crowns tended to disintegrate at the higher temperatures used.

In an experiment using the teeth of domestic pigs (*Sus scrofa*), Hughes and White (2009) found that fracture propagation in dental enamel was similar to that of bone. They observed longitudinal and transverse heat-induced cracks contoured around dental enamel, with dentin presenting greater shrinking and deformation than the less organic enamel. Dental crowns have been proposed to be the only skeletal structures invulnerable to heat-induced metric changes. Despite the fragility and tendency of enamel to fracture after thermal exposure, tooth crowns have been found to undergo little heat-induced size changes compared to other areas of the skeleton (Godinho et al. 2019).

Godinho et al. (2019) observed an increase in the diameters of experimentally heated crowns using micro-XCT. They also demonstrated that the eventual burn changes were merely the result of micro-fracturing that added to the crown's diameter. Regrettably, enamel is frequently absent from burned skeletal remains, because it resists rapid heat events poorly. Unerupted crowns, however, may nonetheless preserve rather well, benefiting from the protection provided by soft tissues and the maxilla/mandible (Godinho et al. 2019; Gouveia et al. 2017).

Essentially, color changes on thermally altered bone represent a gradient of burn intensity and duration from the outside to the inside of a bone (Beach et al. 2008; Buikstra and Swegle 1989; Devlin and Herrmann 2008; Dunlop 1978; Gilchrist and Mytum 1986; Schmidt 2008; Shipman et al. 1984; Stiner et al. 1995; Symes et al. 2015; Walker and Miller 2005; Walker et al. 2008). Color is also used as a criterion to assess unburned areas and to determine the probable location/position of the body in the fire (Symes et al. 2012). In addition, color changes may provide information on the decomposition stage of the remains prior to burning (Keough et al. 2015). Visual color classifications for bones and teeth, as discussed earlier, are attributed to two main processes: carbonization and calcination.

Carbonization

Organic substances contain high proportions of carbon atoms and experience *carbonization* when subjected to intense heat. As the complex organic molecules are broken down and other elements, including oxygen and hydrogen, become volatile and are either liberated into the atmosphere or combine with other elements, carbon remains behind. Naturally occurring carbon is black in color, so carbonized (also referred to as *charred* or *smoked*) bone is also black in color and indicates direct contact with an intense heat source (such as an electrical heating element), burning soft tissue, or flames (Symes et al. 2015).

Other natural (Chapters 7 and 12) and artificial (Chapter 8) processes may stain bone black, so this coloration alone is not always a clear indicator of carbonization. In particular, manganese and/or iron oxides may stain bone in a manner that mimics carbonization (Marín Arroyo et al. 2008; Shahack-Gross et al. 1997). Mineral staining tends to be superficial, while carbonization may either affect the entire thickness of the bone (Symes et al. 2015) or integrate with areas of other color changes, including those resulting from calcination. Fire changes the chemical composition of a bone from an organic to an inorganic material, and thereby reduces its luminescence (Krap et al. 2017). For this reason, external light does not shine through burned bone. The use of an external light on suspected burned bone is a cost-effective and relatively simple method to determine whether the black discoloration on bone is associated with carbonization or not.

Carbonized bone is most similar to dry bone because the organic component (collagen) is largely destroyed; both dry bone and carbonized bone are less durable than unburned bone. Similarly, burned and dry bone is less able to withstand tensile and compressive strain deformation than unburned bone (e.g., Currey 2002; Reilly and Burstein 1974). Carbonized bones are still identifiable, but, unlike dry bone, measurements may not be taken accurately from this material (Thompson 2004, 2005).

With continuous loss of moisture and organic content due to prolonged combustion, bone undergoes significant shrinkage and deformation (Buikstra and Swegle 1989; Thompson 2004, 2005). The rate of moisture loss and bone shrinkage is dependent on many factors including condition of the body (flesh or decomposed), condition of the bone (wet or dry), type and location of material (bone or teeth; cancellous or cortical bone), and the duration of the burn event (DeHaan 2008, 2012; Symes et al. 2012, 2015). For brushfires/grassfires events which are of low to medium temperatures (400°–600°C or 752°–1112° F) and of short duration, Liebenberg (2020) noted that with an increase in the duration of burn, the severity of carbonized areas increased but the degree of shrinkage remained minimal.

Calcination

Calcination is a continuation of the bone combustion process where the liberated carbon from organic molecules combines with oxygen to form carbon dioxide (CO_2) or carbon monoxide (CO) and is freed into the atmosphere (to global detrimental effect). The remaining bone material is comprised of the original inorganic component (hydroxyapatite), consisting of fused bone salts (Mayne Correia 1997; Mayne Correia and Beattie 2002; Krap et al. 2017; Thompson 2004, 2005). The color therefore shifts from black of carbonized bone to white, the natural color of hydroxyapatite, with many possible intermediate color stages (see “Color Changes” section, above) between the two states (Figure 14.2).

Calcined bone is extremely fragile and has an even greater loss of strength than carbonized bone. Heglar (1984:149) described calcined bone fragments as having a fine-pottery appearance, including feel, mass, and sound (when fragments are clinked together or against a hard surface). As bone is heated above 500°C, some hydroxyapatite recrystallization occurs. The average crystal size increases (Hiller et al. 2003) as the temperature increases up to 900°C, ultimately making the overall bone structure more brittle (Stiner et al. 1995). Arc-shaped fragments of cortical bone, such as from long bones or metapodial shafts, easily snap when little pressure is applied. Fracture, shrinkage, and deformation accompany calcination and further weaken the bone structure and integrity. Damage makes skeletal element identification of a calcined bone difficult. As a rule, bone altered to this degree cannot be measured as a part of skeletal analyses, and the potential for DNA recovery is significantly reduced or obliterated (Schwark et al. 2011; Thompson 2004, 2005). Commingling of heavily calcined individuals also becomes extremely difficult to resolve,

Figure 14.2 Gray-blue discoloration of calcined bone with longitudinal fractures and charring. Patina fractures are noted on the surface. Tannish discoloration on top of the calcined bone may be associated with the bone being dry at the time of the burn event (Buikstra and Swegle 1989). (Photograph courtesy of Natalie Keough, University of Pretoria, Pretoria, South Africa.)

as many analytical methods (DNA, refitting, pair-matching, or articulation) are no longer possible. Substantial information on the biological profile, however, may be obtained from calcined remains as long as careful handling and reconstruction are employed (Grévin et al. 1998). For example, despite variable degrees of shrinkage, Gonçalves et al. (2011, 2013) were able to estimate sex by measuring cremains.

Archaeologists have noted that calcined bone may prove more resistant to subsequent diagenetic breakdown in the soil (Gilchrist and Mytum 1986), particularly in acidic substrates which typically destroy bone integrity over time (Chapter 5). This differential preservation potential has neither been tested nor shown to affect remains detectably over shorter forensic intervals.

Effects of Cooking on Bone

Another type of thermal alteration to bone is cooking, various heating techniques designed to raise the temperature of soft tissue and bone which usually occur without actual combustion. These methods include roasting and boiling, the former of which is similar in its effects to the interior tissue of a body exposed to direct flames. Since the taphonomic changes brought about by boiling do bear upon the overall structural degradation of heated bone, possible changes to bone and differentiated cooked and uncooked bone are addressed.

Boiling of bone (which occurs at 100°C at sea level) is relevant to forensics in two contexts: in rare cases of cannibalism involving cooking and as part of the taphonomic suite of alterations common to animal bones, which may aid in determination of nonhuman origin when morphological analysis is insufficient. Long periods of boiling make bone smoother, lighter in color, and more translucent than fresh, uncooked bone (Bosch et al. 2011; Lupo and Schmitt 1997; Roberts et al. 2002), with more subtle changes at lower intervals and temperatures (Koon et al. 2010). In addition, portions of bone collagen may convert into gelatin, which leaches from the bones (Roberts et al. 2002). This method is purposefully employed on a large scale in some food manufacturing processes. A weakening of overall bone structure due to loss of collagen content and integrity also occurs (Roberts et al. 2002). Using SEM analysis, Bosch et al. (2011) and Trujillo-Mederos et al. (2012) noted progressive smoothing of surfaces by the buildup of residues as the boiling interval increased from 2–6 h, although noncrystalline crusts may appear after extended boiling. Bleaching also occurs as the bone is boiled and organic content is leached out (Figure 14.3).

Cooking as a part of cannibalism occurs rarely in forensic cases, but this taphonomic process is found more frequently in archaeology/ethnography. Multiple researchers have provided a suite of taphonomic effects for human remains from archaeological sites which may be used as indicators of cannibalism (Degusta 2000; Flinn et al. 1976; Graver et al. 2002; Hurlbut 2000; Turner and Turner 1992, 1999; White 1992) versus other behavior, including secondary mortuary treatment or trophy-taking (Chapter 8).

Commercial Cremation

Dr. Julius LeMoyne established the first American commercial crematory in the town of Washington, PA in 1876, after multiple attempts in Europe had been unsuccessful. The event was widely reported in various popular and scientific articles of the time (Rosen 2004).

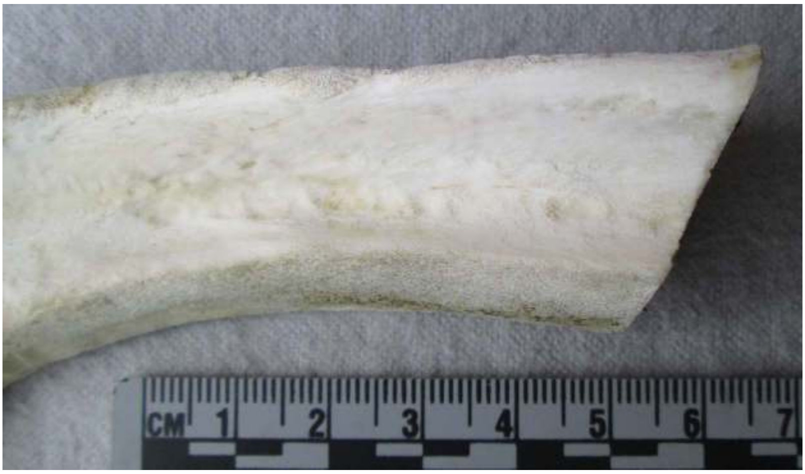

Figure 14.3 Nonhuman rib, boiled for approximately 12 h. Note evidence of bleaching.

This novel treatment of the dead was in stark contrast to and in many cases much cheaper than the elaborate coffins, monuments, and funerals that pervaded nineteenth-century American culture (Chapter 5). Since then, the prevalence of cremation as a funerary option has greatly increased. From 1876 to 1884, only 41 cremations were performed in the USA; in 2001, this increased to 651,176 (out of 2,409,000 deaths or a rate of 27%). In 2019, an estimated 55% (approximately 1,500,000 people) of all American deceased were cremated (Cremation Association of North America 2019).

The practice of cremation is fundamental to Hindu funeral treatment and many other religions worldwide. In addition, some religions prohibit the practice, as in the case of Orthodox or Conservative Jews and Muslims. Only in 1963 did the Second Vatican Council reverse an earlier (1886) ban on cremation for Catholics (Rosen 2004), so some portions of the US population are not represented in the total produced cremains. In tandem with this trend, increasing popularity of pet cremation (U.S. Cremation Equipment 2019) in the USA likely will cause more cases of potential commingling or misidentification in the future. Furthermore, popularity has increased for use of both human and nonhuman cremains to create synthetic diamonds and moissanite gems along with “cremains jewelry”, which is the fashioning of ashes into charms, bracelets, lockets, etc. As expected, the fashion of wearing and collecting cremains will affect the biological information that can, if any, be obtained from cremains cases in the future.

Many states in the USA have approved of the alkaline hydrolysis methods, or biocremation, of human and nonhuman remains. The process liquefies the body’s soft tissue so that it can be easily disposed (Hansen 2012). Biocremation involves boiling the body in lye at 150°C for half a day or until the soft tissues have dissolved. Environmentalists advocate for the biocremation process, as it reduces CO_2 emissions, but many other stakeholders (such as funeral directors) opine that it is a disrespectful treatment of the deceased. Both the Mayo Clinic in Minnesota and the University of Florida, Gainesville, use this method to dispose of their dissection room cadavers. The commercial aspect of biocremation is not as accessible in the USA as traditional cremations, where over 3000 crematoria are available (Hansen 2012). Similar to cremation, biocremation does not destroy bone, tooth fillings, breast implants, or other artifacts (Hansen 2012), suggesting that the taphonomy of alkaline hydrolysis on the skeletal structure of humans and nonhumans remains needs further investigation.

Standard Cremation Procedures

Modern cremations proceed in gas-fired ovens, and the main chamber (the retort) is lined with heat-resistant refractory bricks (Davies and Mates 2005; Ubelaker 2009). The body is placed into the retort and cremated in a container such as a body bag, a simple stapled cardboard box, or a wooden casket (Bass and Jantz 2004). The heat of cremation typically is 1600°–1800°F (870°–980°C), with an average time of 2–2.5 h necessary (Rosen 2004). The duration of heat necessary for a full cremation varies primarily with body mass such that larger individuals take longer to reduce into ash fully. Cleaning of the oven between runs is accomplished by sweeping the retort contents into a steel cooling pan. The likelihood of a slow intermixing of residual ashes among individuals cremated in the same retort does exist, but larger and more visible bone fragments are less likely to be left behind between successive retort runs, and the use of a metal tray under the remains reduces this possibility.

Post-Cremation Processing

To render remains unidentifiable through normal analytical means, cremains are deliberately pulverized after being removed from the retort. Numerous reasons exist for the implementation of this standardized method, but it also reduces the likelihood of civil litigations against the crematorium due to the reduced ability to determine when one set of cremains has been mixed for or with another (Warren and Schultz 2002). While hand methods of pulverization of large bone fragments using mallet-like implements were once common, newer electrical devices dubbed *cremulators* are now frequently used. A cremulator is basically a ball or hammer mill utilized within a rotating drum pierced with 4 mm holes. The cremains are placed inside and are rotated with tumbling metal cylinders or balls to cause crushing. Fragments pass through the drum when they are smaller than the 4 mm outlet holes (Warren and Schultz 2002). The machine tends to produce long slivers of bone along with smaller fragments and dust. The most common type of cremulator uses rotating blades and largely functions like a food processor to produce tiny fragments rapidly (Warren and Schultz 2002). Although little diagnostic bone survives this procedure, it has been noted that most cremated remains will have some bone fragments identifiable to a forensic anthropologist (VanDeest et al. 2012). The size and proportion of cremated remains may be relevant in cases of cremation legitimacy (VanDeest et al. 2012).

Mass of Cremated Human Remains

Burning also results in a loss of bone mass, through volatilization of moisture, breakdown and oxidation of organic molecules, and combustion of fats (Grupe and Hummel 1991; Thompson 2004, 2005). Hiller et al. (2003) reported an overall bone mass loss of 30%–55% with samples of calcined cortical bone. Whole bones are likely to lose a greater proportion of mass due to the large amount of soft tissue (primarily fat contained in marrow cavities and cancellous bone) contributing to their initial, unheated mass. Warren and Maples (1997) found that cremains had a mass approximately 3.5% of pre-cremation adult body mass, and this amount dropped to 2.5% for children and 1% for fetuses. Clearly, bone mineral component is the major contributor to the mass of cremains. The percentage of cremated mass remaining after long bones were defleshed and defatted ranged from 64.8%–66.9% (Trotter and Peterson 1955). Bass and Jantz (2004) measured the average mass of adult cremains obtained from typical commercial cremations (151 males and 155 females) in east Tennessee, USA. The contents of each cremation included the body and usually some kind of container, including body bags, cardboard boxes, and wooden caskets. The cooled oven contents were removed, with any visible large pieces of container or other large artificial objects removed along with ferrous object removal (carton staples, etc.) using a magnet. Masses were determined after extraneous object removal, but some of the ash content must have derived from the burial container and/or clothing. Bass and Jantz (2004) found that the male mean was 3380 g (range: 1865–5379 g) and the female mean was 2350 g (range: 1050–4000 g). Warren and Maples (1997) obtained similar results, notably with adult male and female means separated by 1053 g, while the difference in adult male and female means in the Bass and Jantz (2004) sample was 1030 g. Warren and Maples (1997) also found in their adult sample ($n = 91$) that all cremains masses above 2750 g were male and all below 1887 g were female; notably, their sample uniformly was cremated in cardboard containers. From a much larger sample size ($n = 756$), Van Deest et al. (2011) found that cremains mass averaged 2737.1 g. Males (3233.2 g) were significantly heavier than females (2238.3 g; $p < 0.001$), which is comparable to previous studies.

These masses likely represent a higher degree of incineration and overall body mass loss than would be obtained through most common means attempted for criminal body disposal and also lack soft tissue and significant amounts of carbonized bone (Ubelaker 2009). The lack of large fragments of bone also would distinguish a commercial cremation from most criminal cremations (Baker 2004).

Surgical Implants and Dental Restorations Surviving Cremation

Fortunately for forensic investigations, multiple types of items implanted into human bodies survive both accidental and deliberate cremation and, in many cases, can be used for positive identification (De Angelis et al. 2017). This is especially true where individual serial numbers have been engraved into the object, which is required of all such medical devices of sufficient size since 1993 in the USA (Ubelaker and Jacobs 1995). Even smaller devices such as screws require at least a manufacturer's mark (Ubelaker and Jacobs 1995). Figure 14.4 shows multiple titanium alloy femoral head implants of various manufacturers and configurations, all of which survived the intense heat of commercial cremation completely intact except for surface color change. Warren and Schultz (2002) noted that while large, obvious devices such as these are normally removed (in recent years) from cremains prior to their handover to next of kin, smaller surgical implants including surgical staples used for skin closure, vascular clips, sternotomy sutures, pacemaker leads, and sometimes other pacemaker components are noted, despite crematories recommending their removal prior to cremation (Ubelaker 2009).

Many dental restorations, namely endosseous implants, bridges, and metal meshes; orthodontic braces; orthopedic prosthetics; bone synthesis devices (nails, screws); and cardiac fixtures such as pacemakers, valvular protheses, metal endoluminal stints, and metal sutures can survive both accidental/criminal and commercial cremation (De Angelis et al.

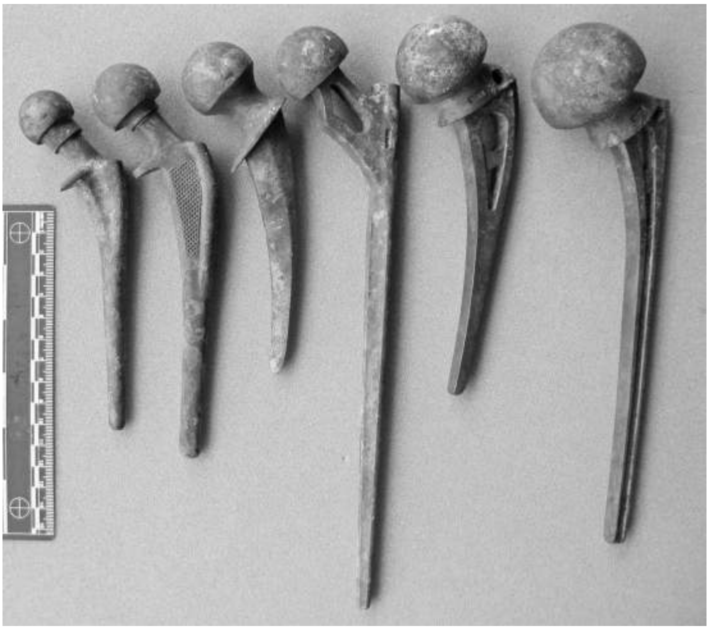

Figure 14.4 Surgical implants (titanium alloy femur head replacements), all of which have survived commercial cremation in excellent condition. The scale is in cm. (Photographed materials courtesy of Ranald Donaldson, University of Victoria, Saanich, BC, Canada.)

2017; Warren and Schultz 2002). Forensic anthropologists should be aware of the type and morphology of available medical devices (De Angelis et al. 2017); this is of critical importance during the recovery of burned human remains.

Distinguishing Cremated Nonhuman from Human Bone

A particular problem when examining cremains is the potential for commingling with animal bones (Whyte 2001). The ability to differentiate human from nonhuman skeletal elements is directly dependent on the condition of the remains on the combustion spectrum. Large fragments, especially epiphyses, can be diagnostic at the species level. However, this becomes more difficult when the skeletal structure has been reduced to ash or unidentifiable fragments. This is particularly true of certain depositional settings such as outdoor burn pits, chimneys, incinerators, or certain accident scenes or vehicles carrying humans and animals together (aircraft, personal vehicles, or commercial transport of animal parts). Analysis of accidental/criminal or commercial cremains may include assessing the minimum number of individuals (if possible) and identification such as pet tags, surgical implantations, and other nonperishable devices (Ubelaker 2009). Under these circumstances, no clear methodology is available in which to address separation of commingled remains that have been reduced in many cases to calcined fragments and are devoid of morphological indicators of species origin. Brooks et al. (2006) suggested that elemental analysis can be performed, but this is more to examine the difference between organic and inorganic components. If bone has diagnostic features and surviving cortical bone, then both morphological characteristics definitive of a particular species and the microstructural layout of cortical bone (histology) are options for distinguishing human and nonhuman fragmentary remains (Hillier and Bell 2007).

Brits et al. (2014) provided a baseline description of histomorphology (vascular canals, primary osteons, and secondary osteons) of southern African animals, including impala (*Aepyceros melampus*), monkey (*Chlorocebus pygerythrus*), baboon (*Papio ursinus*), cat (*Felis catus*), dog (*Canis familiaris*), cow (*Bos taurus*), sheep (*Ovis aries*), horse (*Equus caballus*), donkey (*E. africanus*), and pig (*Sus scrofa*), compared with human. The researchers observed overlap in histological structures among species and combinations of bone tissue types. Diversification of histological structures among species was observed when categorized into their taxonomic order. For example, Artiodactyls (cow, pig, sheep, and impala) all had primary vascular bone, whereas haversian bone was found in carnivores (cat, dog), Perissodactyla (horses and donkeys), and primates (monkey, baboon, and human). While possible to distinguish human from nonhuman bone from their histological microstructure, the large degree of overlap among species may prevent accurate diagnoses when trying to distinguish species based on their histomorphology from bone fragments (burnt or unburnt) (Brits et al. 2014).

Combustion of Whole Bodies: Tissue Shielding and Burned Bone Fracture Characteristics

The rate of destruction of a bone with combustion is dependent on the size of the body or body part, the differential distribution of soft tissue on the body, the position of the body in the fire, and the biomechanics of burned bone (Symes et al. 2015). Therefore, bones with little tissue thickness and direct exposure to fire, such as the frontal bone (forehead), anterior mandible and teeth, and the dorsal surface of the metacarpals, experience greater thermal alteration over the same period than bones surrounded by more tissue, such as the head of the femur. The differential burning of a human body is conditional on the body entering the *pugilistic posture*, a position that is based on the contraction of strong, flexor muscles due to rapid dehydration of muscular tissue (Symes et al. 1999, 2001, 2015) (Figure 14.5).

Patterned Thermal Destruction

Combustion of a body has been shown to occur in a uniform, recognizable, and predictable pattern (Adelson 1955; Bass 1984; Bohnert et al. 1998; DeHaan 2012; Icove and DeHaan 2003; Pope 2007; Spitz 1993; Symes et al. 2015). However, the location and position of the body; the presence of broken bones, dismemberment, restraints, or confinement; the condition of the body (fleshed or decomposed); and the duration of exposure to fire can alter this pattern, thus rendering it abnormal (Fojas et al. 2011; Symes et al. 1999, 2015). When assessed within the scene context, an abnormal burn pattern may provide some information as to the condition, location, and position of the body prior to the burn event.

An unconfined body can transform from a supine to a pugilistic posture within 10 minutes of exposure to fire (Glassman and Crow 1996). This postural change is the result of rapid moisture loss in soft tissues with subsequent contractions of what are the stronger antagonist flexor muscles over the weaker extensor muscles (Adelson 1955; Symes et al. 2015). With continual combustion, the pugilistic posture provides differential protection across the body, a situation that contributes to the manifestation of a *normal burn pattern* (Table 14.1), which refers to the appearance of thermally altered bone consistent with normal tissue shielding, color change, and fracture mechanics (Symes et al. 1999, 2001, 2015).

As the antagonist muscles contract, flexion of the appendicular skeleton occurs (Symes et al. 2015). In the upper limbs, the humerus medially rotates and adducts, the elbow joint hyperflexes, the forearm pronates, the wrist flexes (toward the forearm), and the phalanges curl into a fist. In this position, the dorsal surface of the hand, wrists, and elbows are the least protected joints from thermal damage, whereas the anterior distal humerus and anterior proximal ulna and radius are joints protected longer from destruction (Symes et al. 1999, 2015). Figure 14.6 illustrates the pugilistic posture of the hand making a fist, and eventually losing the posture due to the destruction of the bone joint.

Joint shielding (Table 14.1) indicates that two bones were articulated during the burn event and that the area of articulation protected the surfaces from fire. This phenomenon can be noted anywhere on the skeleton but is not observed in bodies disarticulated prior to burning. In their study, Keough et al. (2015) observed joint shielding on remains in the

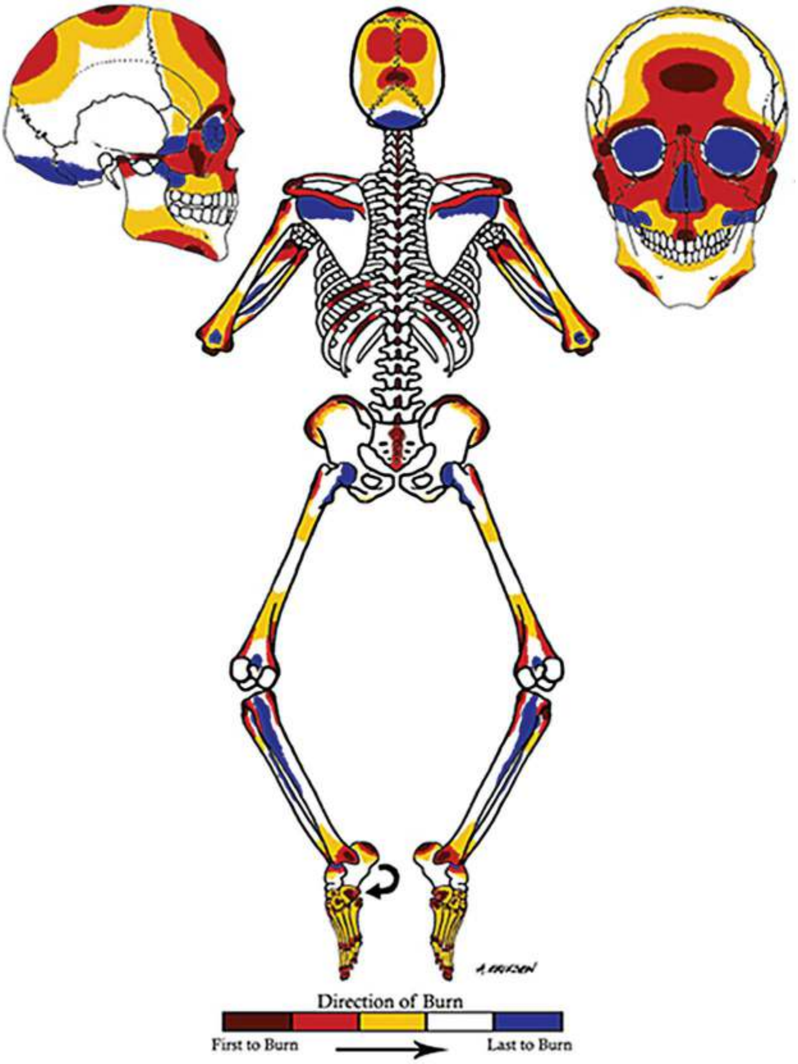

Figure 14.5a Pattern of thermal destruction of a skeleton indicating the initial, secondary, and final areas to express burning on bone, both anterior and posterior. (From Symes et al. 2015:32–33; used with permission, Academic Press.)

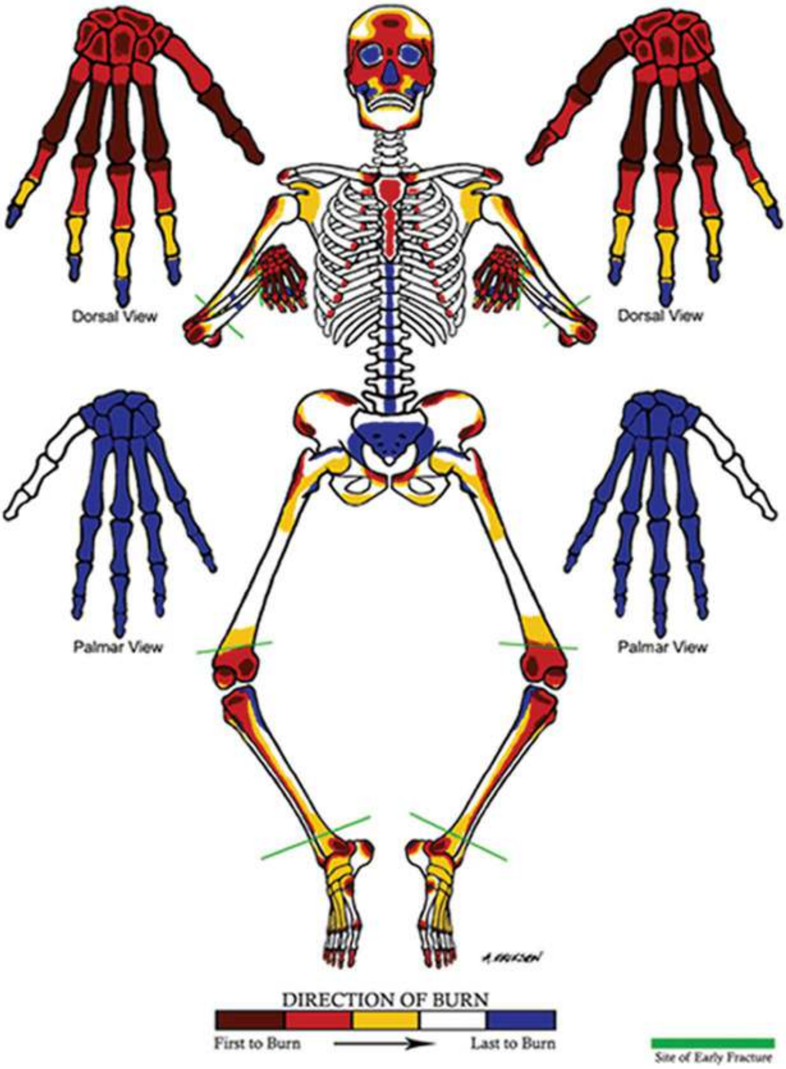

Figure 14.5b Pattern of thermal destruction of a skeleton indicating the initial, secondary, and final areas to express burning on bone, both anterior and posterior. (From Symes et al. 2015:32–33; used with permission, Academic Press.)

advanced and early skeletonized decomposition stages, but not on dry, completely skeletonized remains. Thus, joint shielding is suggested to be more dependent on presence of intact ligaments rather than percentage of soft tissue present. Figure 14.7 illustrates an abnormal burn pattern, where the skull base is the area of initial burning due to its disarticulated position in the South African veldt. Despite advanced decomposition, the burn pattern reveals the presence of possible ligaments, but not necessarily more extensive soft tissue, holding the mandibular condyle in place during the fire.

In the lower limbs, the thigh flexes, such that the anterior knee is exposed, but the posterior popliteal fossa (behind the knee) is protected. The ankle plantar flexes, the foot inverts, and the phalanges flex (Symes et al. 2015). Thermally induced damage progresses generally from distal to proximal on the lower limbs with the dorsal surface of the foot, ankle, medial malleolus and anterior shaft of the tibia, tibial tuberosity, patella, distal

Figure 14.6 Postmortem fracture of the distal metacarpals and proximal phalanges from burning of the knuckles in a pugilistic fist. With the joint destroyed, release of the postured fingers are relaxed and the distal phalanges are exposed to fire. This represents a normal burn pattern where the distal phalanx of the four fingers is the last to burn.

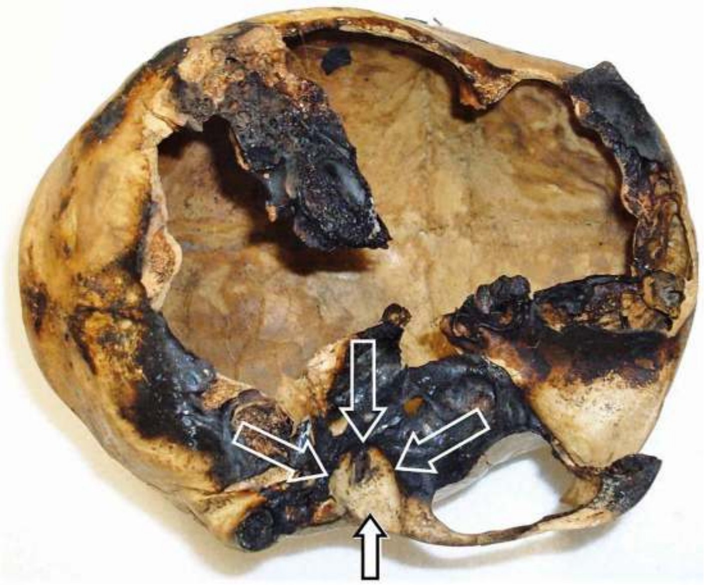

Figure 14.7 Joint shielding represented in a decomposed skeleton discovered in the South African veldt. While the burn pattern is abnormal, the mandible was articulated at the time of burning. (Image courtesy of Marius Loots, University of Pretoria, Pretoria, South Africa.)

femur, and eventually the hip (acetabulum) being destroyed. The first area to be completely compromised is the ankle, followed by the distal femur, just above the knee. The posterior knee is protected in the popliteal region on account of the pugilistic flexing posture (Figure 14.5a).

With regard to the axial skeleton (head and trunk), the head and neck are hyperextended due to contraction of the nuchal muscles (Symes et al. 2015). The face and mandible are consequently exposed to fire, but the area around the occipital bone and neck proper are protected. As the forehead and facial bones are thinly lined with soft tissue and muscle, thermal destruction is initiated at the frontal bone, followed by projecting bones of the face, anterior teeth, and lateral margins of the external mandible. Even though the cheek bones and lateral mandible carbonize early, the face is comparably higher in moisture and is more resistant to burning than either the forehead or the vault. Total destruction of the forehead and skull apex occurs prior to severe burning destruction of the face (Symes et al. 1999, 2015).

Contrary to popular opinion, the cranium does not explode when exposed to continual combustion (Pope and Smith 2004; Symes et al. 1999, 2001, 2015). Once the calvaria is exposed, sutures separate, and darkish brown coagulated masses of boiled (or boiling) blood and fluids often form between the dura mater and the skull (*heat hematoma*). As this is a normal process of thermal destruction, the appearance of dried or cooked blood on both parietals should not be immediately associated with perimortem trauma or injury. The skull often presents with differential areas of carbonized and calcined bone, and the differences can often be recognized as relating to soft tissues and body fluid protection (Symes et al. 2015:40–41, 45). According to Symes et al. (2015), differential distribution of color associated with carbonized and calcined bone in a single skull is due to the various areas of this structure simultaneously experiencing different degrees and duration of heat. In other words, a heterogeneous burn pattern is noted with fleshed remains, with differential burning patterns also observed on the chest and limbs (Williams 2020). Under these circumstances, color changes on bone indicate the duration and gradient of burning.

The trunk and parts of the appendicular body closely associated with the trunk (clavicles, scapulae, ribs, sternum, vertebrae, and pelvis) consist of the largest and heaviest part of the body and tend to survive burning for longer than the head and the rest of the appendicular skeleton. In the pugilistic posture, the shoulders and arms adduct, and the vertebral column hyperextends. The first areas to burn are the sternal ends and midshafts of the external clavicles, the acromion process of the scapulae, the sternum, the anterior ends and lower, posterior external surface of the ribs, and the vertebral spinous processes. The anterior vertebral column and a small area inferior to the scapular spine (infraspinous fossa) are the last to burn. In the pelvis, thermal damage appears on the superior anterior iliac crests followed by the anterior surfaces of the pubic bones (Figure 14.5a,b).

Interpretations of Traumatic Injury from Burned Bone

As discussed in Chapter 13, an anthropologist's knowledge as to the timing of a traumatic injury is paramount for accurate interpretation. The potential for perimortem trauma in burned remains to be identified requires a forensic anthropologist to understand the dynamics of burning bodies as well as the context of the remains and to be able to distinguish between defects inflicted *prior* to thermal alteration and those occurring *as a result* of burning (Table 14.2) (de Gruchy and Rogers 2002; Herrmann and Bennett 1999; Pope and Smith 2004; Symes et al. 2015). The context and condition of the bone and body at the time of burning contribute to the complex questions associated with burning. This section addresses observable fracture patterns on wet and dry bone, the biomechanics of wet and dry bone, and the complexity of perimortem and postmortem terminology when addressing burned remains. Wet and dry bone properties are discussed in more detail in Chapter 13.

Experiments on the retention of bone trauma features of sharp, blunt and high-velocity injuries post-fire is abundant in the recent literature (e.g., Alunni et al. 2017; Campbell and Fairgrieve 2011; Galtés and Scheirs 2019; de Gruchy and Rogers 2002; Macoveciuc et al. 2017; Marciniak 2009; Pope and Smith 2004; Symes et al. 2012). Burn conditions, material (pig vs. human), and methods (outdoor fire, house fire, field fire, closed crematorium burn), however, differ considerably, which make comparison of the research and patterns of thermal-induced changes to perimortem fractures difficult to tease apart. An overarching theme from all these studies is that wet-bone injuries, like morphological features, are probably observable after the burn event. As expected, the ability to observe and to describe a wet-bone fracture from a burned bone is also dependent on the amount of exposure of the bone to fire and the duration of burning (Symes et al. 2015).

Fracture Patterns on Burned Bone

The condition of a body, such as fleshed, decomposed, or skeletonized, and the organic composition of the respective skeletal structure prior to burning contributes to the burn morphology and fracture characteristics (e.g., Baby 1954; Binford 1963; Keough et al. 2012; Keough et al. 2015; Liebenberg 2020; Symes et al. 1999, 2015; Thurman and Willmore 1980–81). With fleshed remains, soft tissue destruction starts at the skin, advances through fat, muscle, cartilage, and periosteum, and eventually reaches bone. Consequently, skeletal elements present with shielding, a greasy appearance (oily texture or appearance), a white heat line, a heat-altered border with predictable cracking adjacent to the heat line, and various heat-induced fractures such as deep longitudinal and transverse splits as well as curved transverse fractures (Figures 14.7–14.9; Table 14.1) (Curtin 2008; Keough et al. 2012; Symes et al. 1999, 2015; Herrmann and Bennett 1999).

Bone does not combust in a uniform manner, even on the same bone. Just as a piece of wood often burns in stages, with some portions reduced to ash, some portions carbonized, and some portions unburned at any given moment, so too does bone. The insulative properties of soft tissue increase this effect. Thermal alteration might be observed only on a small, exposed area of bone and consist only of a *heat-altered border*, where the soft tissue or periosteum, or both, has been burned away to that point. The result of this event is a white to off-white color border with a variable width found between the heat line and carbonized bone (Symes et al. 2015). The exposed border of the bone is visibly affected, but the bone not visibly affected also has undergone some dehydration and molecular alteration. The heat-altered bone is usually opaque, while in unburned fresh bone, the change appears translucent (Symes et al. 2005, 2015). Visible damage associated with the heat-altered border may include heat shrinkage fractures, flaking, or distortion of the outer cortical layers (Table 14.1), and brown discoloration due to exposure to heat and possible flame but not to the extent that the bone has become carbonized (Symes et al. 1999, 2015). In addition, a *white heat line* is sometimes found adjacent to the heat-altered border

Table 14.2 Fracture Class I to III for Identifying Wet vs Dry Injuries from Burned Remains

Fracture Class	Definition	Characteristics	After-Burn Clues of Bone Fractures
I Fresh, Wet Bone	Fresh (organic) bone, with well-preserved, clear microscopic morphology.	External impact, plastic deformation; consistent with a dynamic load. Evidence of morphological traits associated with tension, compression is visible. Plastic deformation, delamination, radiating fractures, concentric-in fractures (cranium), angled bevel and a final bone tear.	Disruption in the normal pattern of heat-induced changes to a fleshed body. Seen on bone with: • Location of burn • Pattern of burn (color) • Radiating fractures running from burned areas • Incisions or sawing into bone • Ballistic defects, plug/spall, radiating fractures, high energy
II Drying Bone	Outline and location are typical of *in vivo* breakage, but fracture mode and dynamics cannot be conclusively substantiated from the burned material	Tension-compression markers cannot be identified on account of the burn event, but sharp force and ballistic injuries may still be identifiable.	Bone is in the process of changing from a viscoelastic material (organic) to a dry and brittle (inorganic). • Radiating fractures running from unburned areas • Color changes in bone weathering • Location/anatomy of fracture could possibly suggest injury prior to burn • Incisions or sawing into bone • Ballistic defects, plug/spall
III Heat Induced	Static bone fractures associated with the burn event	Associated with all heat-induced changes to bone such as color change, weight loss, and change in bone strength. The fractures mark the passage of bone from a viscoelastic to a dry, brittle material.	Fractures • Curved transverse • Longitudinal • Transverse • Patina • Coning • Fractures remain within the burned area

Source: L'Abbé et al. (2015) and Symes et al. (2015).

(Gough et al. 2021; Symes et al. 2015) (Figures 14.8 and 14.9). The white heat line is generally narrower than the width of the border and appears as a transitional zone between burned and unburned material (Figure 14.8).

White heat lines have been associated exclusively with fleshed or wet bone, especially when wet bone has adhering soft tissue (Gough et al. 2021; Liebenberg 2020). Gough et al. (2021) examined experimentally the presence/absence of white heat lines in five different bone conditions: fleshed, defleshed/very wet, partially wet, dry, and dry/soaked. Source

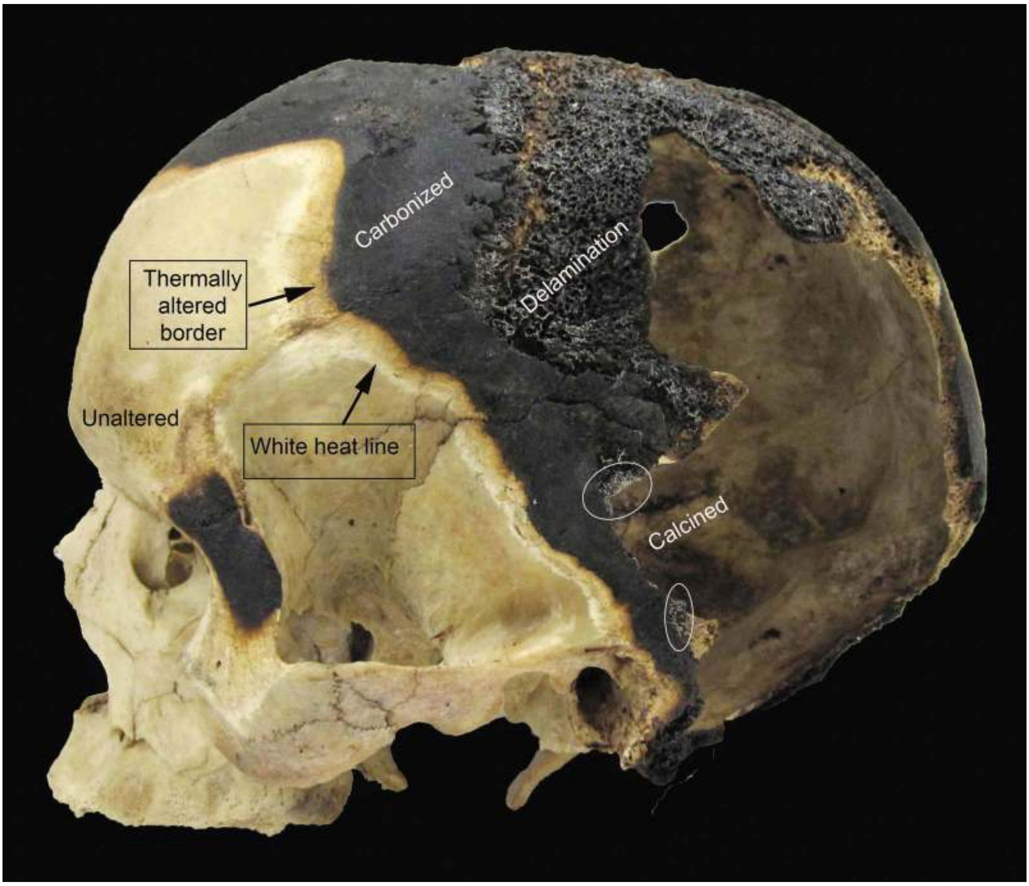

Figure 14.8 White heat line, heat border, charring, and delamination observed in a case of "necklacing" from Kimberley, South Africa. The abnormal burn pattern is possibly due to perimortem injuries on the face and mandible as well as location of the tires. Necklacing is a type of execution that originated as a form of vigilante justice against Apartheid conspirators in the townships in the mid-1980s. Two or more tires (filled with gasoline) are placed around a victim's chest and arms, and the person is set on fire (Bornman et al. 1998). (Image courtesy of Natalie Keough, University of Pretoria, Pretoria, South Africa.)

material included elk (*Cervus elaphus*), white-tailed deer (*Odocoileus virginianus*), pig (*Sus scrofa*), and sheep (*Ovis aries*) bones which were exposed to a natural wood fire. The presence or absence of heat lines was assessed through macroscopic visual analysis and then examined with Fourier Transform Infrared Spectroscopy. No white heat lines were observed in the partially wet, dry, and dry/soaked samples, whereas white heat lines were present in 29.6% of the defleshed/very wet and in 50.0% of the fleshed samples. The width and shape of the white heat lines varied, with fleshed bones having a more uniform, defined, and sharper color and the defleshed/very wet bones having a more irregular width and shape as well as being accompanied by a heat-altered border.

Heat-altered cracking can be predictable within a heat-altered border. These fractures are found at the transition area between the heat border and the carbonized area and are a result of dehydration from heat exposure, which causes bone to shrink and crack within the tissue border. Heat-altered cracking can also be quite minimal and present as non-distinct,

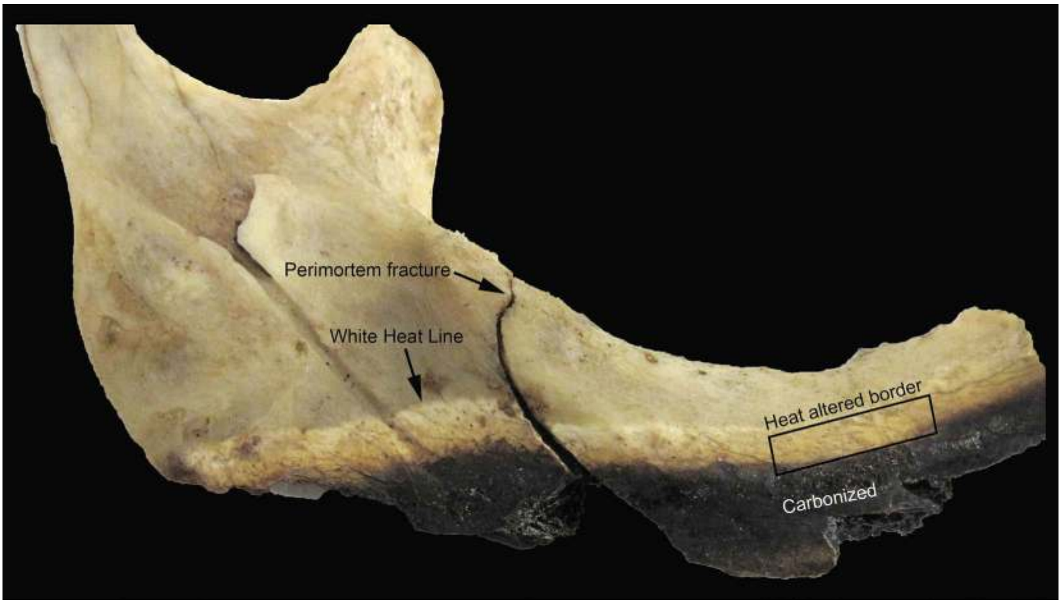

Figure 14.9 White heat line, heat-altered border and predictable cracking within this border, and carbonization are observed on the mandible associated with a case of "necklacing" from Kimberley, South Africa (Figure 14.8). Note perimortem injury that traverses the unburned and burned areas. (Image courtesy of Natalie Keough, University of Pretoria, Pretoria, South Africa.)

random fracture lines (non-parallel) within the heat altered border. These fractures are not associated with the mechanisms that create predictable fractures but are attributed to direct exposure of the bone to fire.

Few heat-altered borders, white heat lines, or heat-altered cracking are recognized in bones that are skeletonized prior to burning. Little distinction is noted between burned and unburned bone in dry bone, with little observable micro-fractures or warping (Figures 14.10–14.13) (Keough et al. 2015; Liebenberg 2020). Dry bone directly associated with the fire initially becomes brown in color; with a longer burn duration, the bone becomes black, or carbonized, and then calcined. Liebenberg et al. (2020) noted dry bone carbonized and calcined faster than wet or fleshed bone.

Curved transverse fractures, or thumbnail fractures (Table 14.1), were initially observed in bodies associated with house and car fires (e.g., Symes et al. 2015). Researchers suggested that these formed by heating and cracking of wet bone as kinetically charged protective soft tissues (muscles) and periosteum shrink away from their attachments and expose a new surface to direct heat. The curved defect reflects the partially destroyed end of a muscle or other tissues as they shrink toward the unburned end (Symes et al. 1999, 2015). Shrinking muscles that appear to create these "trailing" fractures, however, do not necessarily create a curved shape, especially if wide muscles, like the nuchal muscles, are being destroyed (Symes et al. 2015:47–50).

Less commonly, the curved transverse fractures appear as concentric rings in fossae or simply areas of concentrated tissues, such as the popliteal region of the femur, of bodies associated with car and house fires (Figure 14.14). This type of fracture is the result of a combination of factors such as cortical bone thickness, bone shape, articulation, and soft tissue obstruction, as well as gradual muscle retraction. Concentric rings can also form in

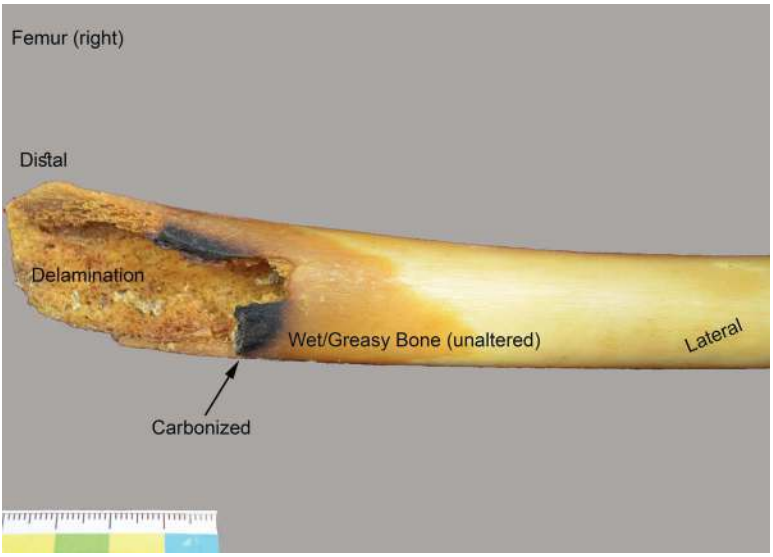

Figure 14.10 Carbonization on wet/greasy bone of the right femur, indicating a low temperature and short duration of burning that is consistent with grassfires in South Africa. The scale is in cm.

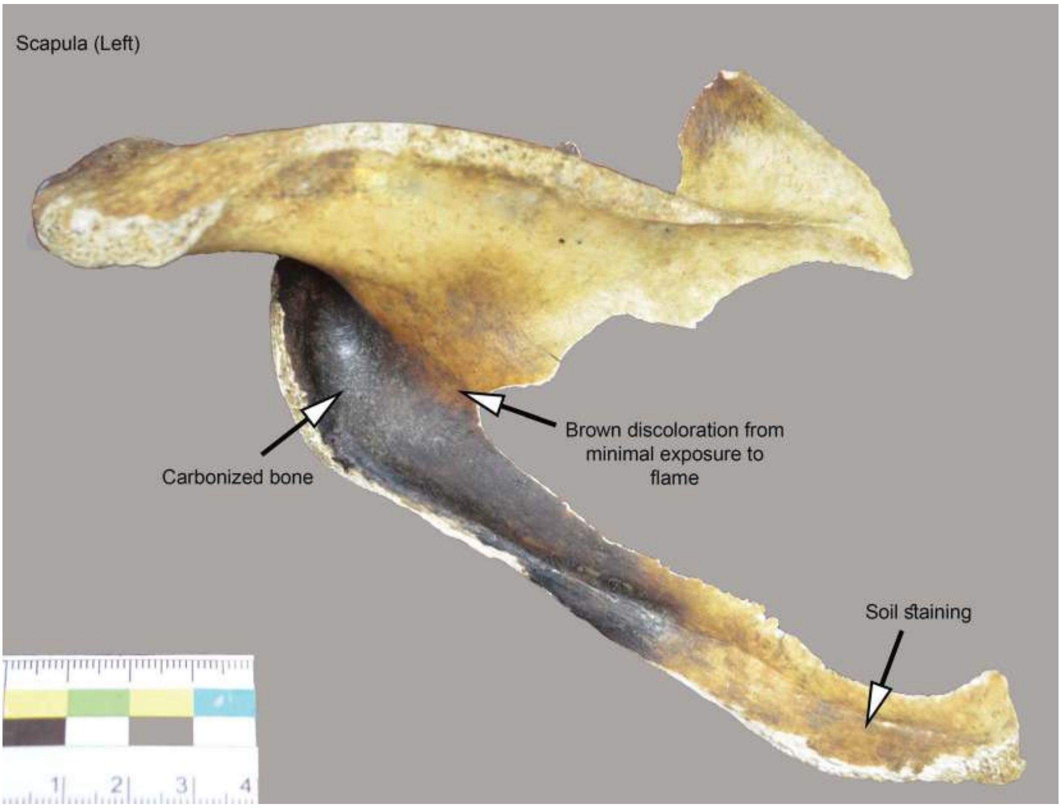

Figure 14.11 Carbonization on the left scapula found in the South African *veldt*. Soil staining is observed with carbonization. No white heat-line is present gradual separation between burned and unburned areas. The scale is in cm.

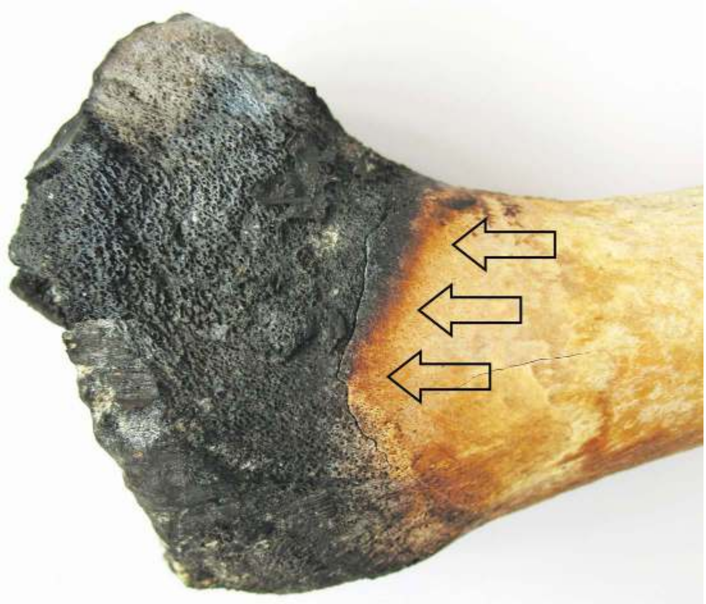

Figure 14.12 Irregular charring, longitudinal fractures, and absence of a heat line on wet/dry skeletal remains discovered in the South African veldt, with an abnormal burn pattern.

Figure 14.13 Carbonization and an irregular burn pattern on the mandible. Note longitudinal fractures within the burned area and the absence of a white heat line.

flat joints, where little soft tissue exists. As distorting tissues further strain joints (that are subjected to heat, joint manipulation, and gradual movement of the bones) out of articulation, concentric fracture rings are suggested to occur. Figure 14.15 illustrates the first proximal foot phalanx articular surface with curved transverse fractures illustrating a burn pattern of slow encroachment into the joint. Encroachment is dependent upon the distal metatarsal and proximal phalanx's slow separation due to soft tissue shrinkage.

Figure 14.14 Curved transverse fracturing noted on a distal femur shaft. The concentric fractures along the bone are an indication of the direction of burning. This pattern represents the last bastion of soft tissue to succumb to heat destruction.

In long bones, curved transverse fractures commonly result in *coning*, where the fractured diaphysis appears arched at the fracture margin. Figure 14.16 illustrates classic thermal destruction to fleshed bone. The distal humerus is exposed and is the initial area to burn on this bone. This example shows a distal third of the shaft from an anterior and posterior view. This bone has more thermal damage distally as opposed to proximally, as indicated by color. The distal humerus burns first and then slowly burns up the shaft of the arm. The curved transverse fractures indicate the direction of burn, and failed curved transverse fractures reveal coning, where the bevel indicates the direction of the burn as well, due to the external burning of bone first and internal burning last. In addition, the external calcined and internal carbonized color indicates that the bone was intact and burning from the outside in as well as distal to proximal. However, in recent research Gonçalves et al. (2011) did not exclusively observe curved transverse fractures on fleshed or wet bone and in fact observed warping and curved transverse fractures in bones that had been buried for years. Therefore, they suggest that this variable should not be exclusively used to distinguish whether the body was fleshed, wet, or dry prior to the burn event. The number of exceptions in their sample were rare, but, nonetheless, some curved fractures appeared on previously buried and possibly dried remains. The present authors agree with Gonçalves et al. (2011) that a more in-depth study of curved transverse fractures is needed, especially in the evaluation of the appearance of curved transverse fractures and

Figure 14.15 The first proximal foot phalanx joint with curved transverse fractures and illustrates a burn pattern of slow encroachment into the joint.

its association with the temperature and duration of the fire, e.g., car fires/house fires and cremations. All researchers agree that curved transverse fractures are found exclusively with burned remains.

With less organic material and soft tissue protection, dry and wet bones have been shown to burn as a more homogeneous unit than fleshed bones. Unfleshed bone carbonizes and becomes calcined more quickly than fleshed bone. A brown line, representing initial carbonization or organic venting, is often noted between heat-altered and unaltered areas and curved transverse fractures are minimal (Figures 14.10–14.13 and 14.17) (Gonçalves et al. 2011; Keough et al. 2012, 2015; Symes et al. 1999, 2001, 2015).

The differences in fracture morphology between fleshed and dry/wet bone are associated with differences in the biomechanical properties of the bone prior to and during burning. Fleshed bone shrinks and warps due to a loss of moisture and collagen; the same process occurs in semi-wet to dry bone but to a lesser extent. Because the process of a bone losing moisture—or transitioning from a wet to dry state—is a continuous process, fracture differences between wet (unfleshed) and dry bone may be difficult to decipher (Chapter 13). Contrarily, a

Figure 14.16 A burned humeral shaft, back (left) and front (right). Note the posterior patina pattern mixed with transverse and longitudinal as well as curved transverse fractures. Distal end (top) represents coning while the proximal shaft (bottom) reveals negative coning, indicating a normal burn pattern.

fleshed body in a hot fire, such as a car or house fire, presents with a unique pattern, as various soft tissues need to be destroyed along with bone, a situation that presents a unique sequence to the burning event. Until recently, our interpretation of these fracture patterns has been based purely on visual inspection and less on an understanding of burn context.

Williams (2020) quantified heat damage on 87 bodies of fatal fire scenes in structures (houses), confined spaces (e.g., burn barrels, trunk of cars), and outdoors settings. The research experimentally burned fleshed human bodies (donated cadavers) to investigate the effect of external variables (location of a body, time, temperature) against the condition of the head, chest and limbs of the body. Thermal damage was scored as a total body score (TBS). TBS scores were highly dependent on environment, duration, presence or absence of ventilation, and temperature of the fire (Williams 2020). Using TBS, duration, and temperature, Williams (2020) created two classification models estimating fire environment and time since death. The first model captured 84% of the variation present within

Figure 14.17 Carbonization, minimal heat-induced fracture and absence of both a heat line or heat-altered border on dry skeletal remains with decomposition staining discovered in the South African veldt. (Image courtesy of Marius Loots, University of Pretoria, Pretoria, South Africa.)

the burn events and provided a 70% classification rate, with misclassifications most often noted for structure fires (houses) and outdoor contexts. The second classification model for time since death was less accurate and only accounted for 25% of the total variation present (Williams 2020). The study contributes to quantification of morphological features observed on a body in a fire and can inform forensic investigators of the postmortem chain of events and to the possible timing of a burn event.

Similarly, Pope et al. (2021) noted differential burning of head, limbs, and chest of donated cadavers exposed to fire. They concluded that investigators need to consider the degree of tissue and bone damage on these body parts separately when creating any possible classification equations that can be used to estimate the fire environment, condition of the body and duration of burning. Both studies open up additional avenues of investigation of body parts and bone in thermally induced events.

Thermally induced fracture characteristics noted in all bones, regardless of prior burn conditions, include longitudinal, transverse, step, and patina fractures as well as delamination (Figures 14.2 and 14.8; Table 14.1) (Symes et al. 2015). Longitudinal fractures are found in long bones and are considered common due to the fact that longitudinal failure is expected with the rapid shrinking of a tube-like shape. This is similar to burned skin patterns on the arms of fire victims. When the bone heats to the point of evaporation and protein denaturation, the matrix shrinks, and structural failure occurs, and often following the grain of the bone. While this failure is often parallel to the Haversian canals, longitudinal fractures also may spiral helically down the long axis of the bone. These fractures occur superficially in cancellous bone due to a completely different biomechanical response to shrinkage.

Transverse fractures are commonly a product of tissue shielding: as fire and heat progress up the bone shaft, the area rapidly shrinks along the line of retreating tissues. Transverse fractures accompany longitudinal fractures and transect Haversian canals. These fractures should not be confused for wet-bone sharp trauma if examined under a microscope. With magnification, tension shrinkage fractures are visible as opposed to incised wounds.

Figure 14.18 Step fracture on the midshaft of the left distal femur. A combination of transverse and longitudinal breaks in the bone, note surficial burning of the cortex. The scale is in cm.

Longitudinal and transverse fractures may combine to form *step fractures*, which extend from one margin of a longitudinal fracture transversely across the bone shaft until they terminate in another longitudinal fracture (Figure 14.18 and Table 14.1). *Patina fractures* appear as a fine mesh of uniformly patterned superficial cracks similar to those seen in old china or an aged painting (Figure 14.16 and Table 14.1) (Herrmann and Bennett 1999; Krogman 1943a, b). They are often observed on flat areas of postcranial bones and may be the result of a broad area receiving uniform amounts of heat. Others have suggested that this pattern is due to the incineration of thin protective soft tissue. *Delamination* and bone splintering are also common and are characterized with the splitting away of cortical bone layers from cancellous bones, the separation of the inner and outer tables of cranial bone exposing the diploë (Figure 14.8 and Table 14.1), or the exposure of cancellous bone on epiphyses. This should not be confused with blunt force injury (or vice versa).

Thermal Destruction of Remains in a Brushfire/Grassfire

In cases of remains recovered outdoors, both normal and abnormal burn patterns can be present on one individual. We use normal and abnormal patterns in reference to the burn patterns observed on bodies burned in car and house fires (Symes et al. 2015). Variation in burn patterns is due to body decomposition and the complete unpredictability of the fire which is based on the environment. This makes analysis of remains recovered from a brushland or grassland difficult and often confusing to the analyst, when comparing their findings to burn patterns from house and/or car fires.

The nature of the fire is dependent on the surrounding vegetation and climatic conditions. For example, vegetation that is dry is often highly flammable and will result in a hot fire, but the duration is shortened due to the fast fuel consumption. A fire that is fueled by oilier vegetation may take time to ignite, but the duration is prolonged due to the increased source of fuel from the plant substance. If vegetation is lush and wet, a fire may not even ignite. A strong relationship is seen between fuel source and duration of the burn event such that if the fuel source is limited, then the duration of the fire is reduced. Climate will also affect the duration of the fire. In windy conditions, a fire may spread over a large area in a short period, minimally affecting remains. Non-windy conditions do not accelerate the spread of the fire, thus areas may be exposed for longer durations. Similarly, a body may be exposed to the fire longer. The same patterns are true for environments that are dry versus wet and rainy (Cheney et al. 2012; Stephens et al. 2018).

As stated earlier, condition of the body plays a major role in manifestation of burn patterns. Decomposing bodies may only assume a semi-pugilistic posture or none at all (Keough et al. 2015). As soft tissue starts to degrade, and tendons and ligaments no longer form strong attachments over joint surfaces, the resulting thermal alterations may appear abnormal when compared to fleshed remains. For example, elements that would normally be exposed last to fire when following a normal burn pattern (e.g., the femur head) may be burned simultaneously to areas which are usually burned first, depending on the stage of decomposition. In addition, body positioning is still an important factor to consider in brushlands. Areas of the body that are in direct contact with the ground may not display any signs of fire damage, thus rendering an abnormal burn pattern. The opposite body surface (that is exposed to the fire), however, will undergo thermal alteration. Understanding the context of the remains and the environmental conditions may assist in interpreting burn patterns. The variables noted above should be taken into consideration when analyzing skeletal remains that have been recovered from outdoor contexts.

In an experiment recreating a brushfire/grassfire, Liebenberg (2020) assessed osteometric changes to domestic pig femora. The wet bones experienced greater levels of shrinkage (up to 7.78%) compared to dry bones (up to 3.98%). Similarly, the areas that consisted largely of cancellous bone, such as the epiphyses, demonstrated more shrinkage than areas with more cortical bone.

With an increase in the duration of burn, the severity of the carbonized areas increased, but the degree of shrinkage remained minimal such that carbonized bones associated with a brushfire fire can be accurately measured for estimating sex from both wet and dry bone. On average, fresh femora differed 4 mm, whereas dry femora differed 2 mm between pre- and post-burn measurements. As expected, the condition of the bone and duration of the burn event (5–20 minutes) had the biggest influences on difference in the bone measurements (Liebenberg 2020). Standard measurements were collected from carbonized human femora associated with forensic cases from veldt fires. Sex was estimated using the measurements from the carbonized remains and was compared to estimated sex from other non-burnt skeletal elements. For limited carbonization on femora, sex estimation was accurate in 93% of the cases. Therefore, forensic case analysis on bones associated with brushfires/grassfires with limited thermal alteration is possible (Liebenberg 2020).

Wet and Dry Bone: Thermal Fracture Characteristics

As stated in Chapter 13 of this volume, forensic anthropologists and pathologists differ in their use of perimortem and postmortem terminology in bone trauma analysis, which also includes thermal destruction to bone (Galtés and Scheirs 2019; Symes et al. 2012). While medical examiners are primarily concerned with changes occurring to soft tissues, forensic anthropologists are limited to defining changes to the condition of bone with or without the influence of other tissues. The fact that the physical condition of bone changes at a different rate than that of the soft tissues further complicates the issue of trauma analysis, with forensic anthropologists assessing condition of the bone, such as fresh, wet, dry, or degraded, at the time that the defect occurred, which may or may not coincide with the death event (Nawrocki 2009; Symes et al. 2015). From an anthropological perspective, the perimortem period may extend as long as the condition of the bone remains moist and retains its viscoelastic properties; this sharply contrasts with the medicolegal definition, which is mainly limited to the time at or around the death event (Chapter 13).

Thermal modification to bone provides another layer of complexity as the normal transition in biomechanical properties from viscoelastic to brittle is accelerated. The accelerated loss of organic content in bone under thermal alteration results in a unique distinction of perimortem and postmortem definitions. The response of thermally modified bone to stress is entirely different from the viscoelastic response of fresh bone. Fractures due to the drying of bone under intense heat are *biomechanically* postmortem, as they occur in bone that is, or is almost, devoid of organic content (Galtés and Scheirs 2019; Symes et al. 2015), where the structure fracturing is not viscoelastic bone. Heat-treated bone is a different material than fresh bone. Furthermore, in contrast to normal decomposition, soft tissue plays an active role in the prolonging of bone modification during burning.

Now that burned bone has been identified essentially as a nonliving, nonviable "non-bone," the authors acknowledge that labeling all thermally altered bone fractures as postmortem is inaccurate. Labeling burned bone fractures in a fatal house fire as "postmortem" neglects the observable conditions of the bone prior to burning. If all burned bone fractures are termed "postmortem," this description ignores details of the burned specimen that relate back to the circumstances of the victim at the time of the fire (Galtés and Scheirs, 2019; Symes et al. 2015).

For example, imagine a hypothetical fire that destroys a small county morgue. All employees evacuated the building but a fleshed body remained on the autopsy table after evacuation. After a major fire destroys the morgue, anthropologists are called in to recover all deceased victims housed in the morgue prior to the fire. Only two bodies are known to be in the morgue that day, the one left on the autopsy table and one dry skeleton laid out in anatomical position on a gurney. The bones belonged to a single human collected from a construction site that accidentally disturbed a grave within a historic cemetery.

The recovery is simple; the anthropologists systematically remove the extensively burned fresh body on the autopsy table, being careful to get all visible fragments of calcined bone. They also recover a dry burned skeleton on a badly burned gurney. Anthropologists should be able to separate the skeleton from the fresh body. If we assume that heat-induced fractures are present on each skeleton, we can probably recognize differences in fresh and dry skeletal remains (as discussed above).

The anthropologists recognize features on the fresh body, possible curved transverse fractures, coning (curved transverse fractures that are separated), white heat lines, thermally altered border with microfractures, and carbonized and calcined bones. The features create expected patterns that suggest that the body conformed to the pugilistic posture and burned, in this case, in a typical fashion. These patterns are strong indicators that the body was fleshed when it burned, not to mention that a bit of torso (flesh) survived the fire. Everything is as expected. Examination of the dry bones reveals different fracture patterns. The bones are not severely fractured; warpage is reduced and curved transverse or coning patterns are less likely to be present. Furthermore, the bone is a different color than the fresh burned bone, as brown soil staining persists, even after the bone is burned.

Obviously, bone carbonizes and calcines in intense heat, no matter the prior burn condition, but the dry bones in this example appear to be the product of a postmortem event. Under a microscope, heat damage causes the bones to fracture, although their reaction is different from that of fresh bone and they fracture similar to dry, brittle bone.

While fractures on the fleshed body and dry skeleton are classified as originating from a postmortem (after death) fire event, the dry bones are altered only after they have dried (Galtés and Scheirs 2019). The fresh body, when considered as a whole, obviously presents characteristics of perimortem destruction, where features of tissue destruction, shrinkage, and organic tissue removal from bone which quite obviously passed through a fresh stage and ended, in some areas, as calcined bone. This was a perimortem event, and our classification of perimortem burning indicated not only fresh bone but that a fleshed body was present before the fire.

While the aforementioned characteristics are helpful in describing postmortem changes to thermally altered bone, the potential for fire to disguise or create "evidence" is of critical importance in evaluating cause or manner of death and can be elucidated if the forensic anthropologist understands the dynamics of burning bodies. A crucial element to distinguishing the timing or sequence of fractures in thermally altered remains is the identification of specific morphological features that differ between perimortem and thermal fractures. Fire has such destructive properties that it can mask or destroy perimortem trauma; or worse, it may create trauma that experts mistake for perimortem (before fire) damage to bone. The repercussions of testifying in court with postmortem trauma portrayed as perimortem trauma are enormous.

Case Study 1: Perimortem versus Postmortem in Thermal Modification

One author (SAS) examined a case that exemplifies the issue of distinguishing perimortem vs. postmortem trauma. In this case, three areas of fracture morphology, fracture initiation/termination, and overall "texture" of the exposed surfaces were essential in determining a perimortem insult. This same approach can be used when interpreting trauma after the taphonomic influence of fire.

A burned-out car was discovered near a small river in the southern USA. The vehicle was eventually traced to a young female who had been missing for several months. A search of the area around the car ensued, only to find a burn pit with debris that consisted of small fragments of human bone, remnants of charcoal, and a burned tire. The scattered remains were eventually identified as belonging to the owner of the car.

Cause and manner of death were unknown in this case, but foul play was obviously suspected by the investigators. While not much of the skull was recovered, a fragment of the right parietal displayed a fairly straight fractured edge with bevel. The suspicious skull fractures and attempts to disfigure and hide the body and car were suggestive of a violent cause and manner of death. These issues were presented to the chief medical examiner. The complexity of the scene and paucity of remains prompted the forensic pathologist to defer this case to an anthropologist for an additional opinion.

Upon receipt of the evidence, the anthropologist realized the daunting task of sorting remains that were extremely fragmented and all, to some extent, thermally altered. Many of these bones, including the aforementioned parietal, were carbonized and calcined, indicating a long-period and/or high-temperature burning. Burned and decayed muscle tissue also was observed with the skeletal remains.

As seen in Figure 14.19, many areas of the skeleton were absent. While the bones were sorted anatomically, burn and fracture patterns were difficult to visualize in extremely fragmented remains. To assist this pattern recognition, Figure 14.20 illustrates the location of identifiable fragments in the body. The core of the body was minimally represented with a few damaged pieces of bone.

Figure 14.19 Skeletal remains of the victim, Case Study 1. Note the extreme fragmentation of the bones, and, while varying in degree, all bones are thermally altered. Many bones are charred or calcined, indicating a long period and/or high temperature burning.

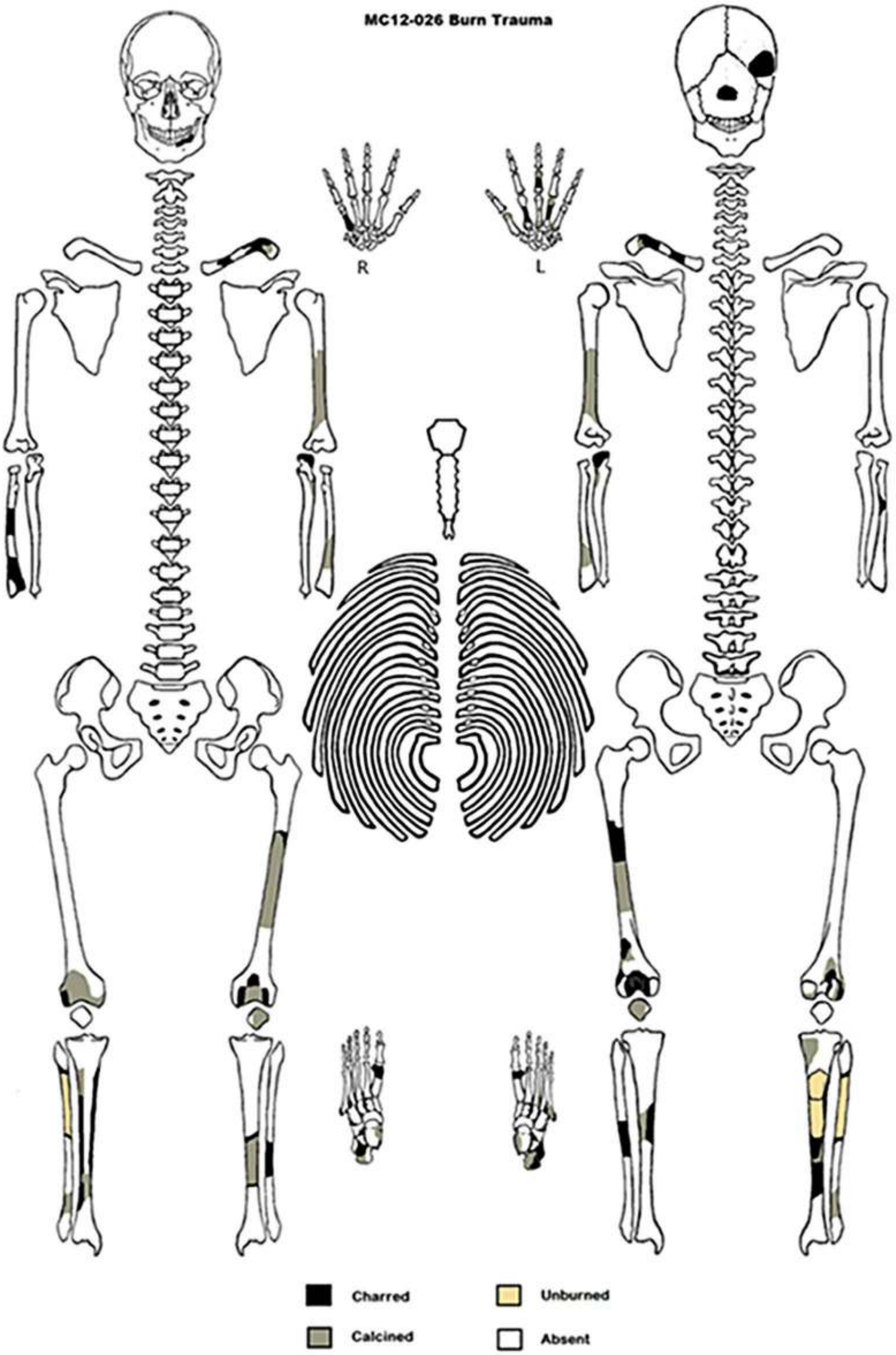

Figure 14.20 Skeletal diagram, Case Study 1, of the location of the bone fragments in the skeleton, illustrating the degree of burning, case study: no burn (beige); charred (black); and calcined (gray). If the bone is absent, then no color is given. Note the complete absence of bones associated with the torso.

With the sparse representation of bones from the axial skeleton—neck, proximal limbs, abdomen, and pelvis—one must consider two possible scenarios. The torso contains the densest area of soft tissue and fluids in the body and is the most difficult area to burn. With little evidence of these bones at the scene, the torso may not have burned effectively, and the perpetrator may have removed recognizable portions of the body from the scene and dumped them in another location or in the river. Alternatively, it is possible that the body was located on a large amount of fuel and accelerants such that the torso was burned beyond recognition, and the outlying areas of the head, neck, arms, and legs were outside the hottest source of fuel and accelerants, were slower to burn, and remained recognizable.

The latter scenario seems unlikely in that almost no bones were found from the core part of the body. Admittedly, a professional osteologist/archaeologist did not perform the recovery, but no representation of these bones seems impossible, especially with a low "campfire" approach to burning a body. The first scenario is most likely to be accurate in that an inexperienced perpetrator attempted to burn a fresh body. Initial attempts severely damaged the top of the head but with enough of the core present to be identifiable as human, the perpetrator likely removed it and dumped it remotely.

The anthropologist's findings were summarized in a report as shown in Table 14.3. The different terminology among experts is of note. Most experts were involved before the anthropologist considered the burning event to be postmortem. Obviously, law enforcement recognizes the fire as an attempt to hide or destroy evidence after a suspected homicide. The medical examiner recognizes a body completely burned and knows physiologically that this was a postmortem event. However, as indicated in Table 14.3, the anthropologist immediately refers to the burning of the body as "perimortem trauma." While investigators and medical personnel realize that the fire likely occurred after death, anthropologists are tied to their medium (i.e., the human body or in this case the remaining fragmentary bones), and the burn patterns on this body are indicative of a severely burned fresh body with fragmentary damage to all limbs and the top of the head. Unrelated processes like burning and weathering dehydrate bone at different rates and eventually damage bone. Fractures due to weathering are considered postmortem. Table 14.3 also summarizes postmortem influences on the body.

Table 14.3 Summary of the Examination of Fragmented Bones Associated with Burned Remains Case Study 1

Summary Examination of Burned Bone	

Human skeletal remains found in suspicious circumstances; burned, scattered, and associated with a burned car and tire.	**Perimortem Trauma**
	• Thermal alteration to tissues
	• Burning occurred to fleshed bone
	Postmortem Trauma to Skull
	• Deterioration of bone due to extreme heat including:
	  • Fracturing and fragmentation
	  • Exposure of trabecular bone
	  • Delamination
	  • Discoloration of all features of perimortem thermal destruction
	Overall Appearances and Inventory
	• Deterioration of bone due to weathering
	• Body core appears to be missing

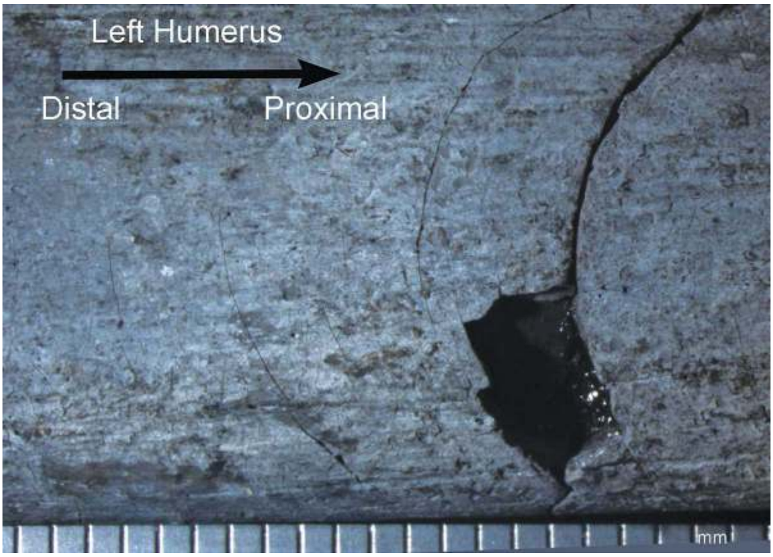

Figure 14.21 Curved transverse fractures from the distal left humerus shaft, Case Study 1. The black arrow indicates the direction of burn from distal to proximal. As expected, the curved transverse fractures progressed up the shaft where the elbow (distal) was exposed early, and the shoulder (proximal) was exposed last.

Most of the recovered skeletal material showed perimortem burn characteristics as evidenced in wet bone color changes that occurred before the bone dried, evidence of grease in the lesser-burned bones, and a normal pattern of thermal bone destruction (Symes et al. 2015). Figure 14.21 shows the distal left humerus shaft. As expected, the curved transverse fractures progressed up the shaft where the elbow was exposed early and the shoulder was exposed last. This is one example of soft-tissue-related fractures that sequentially burn and fracture bone as expected in a normal pugilistic posture, although some (Gonçalves et al. 2011) oppose these theories associated with curved transverse fractures.

The anthropologist's report summary suggested that features and characteristics on the bone indicated a fleshed body in a fire, but the question remained as to whether wet-bone fractures can be attributed to trauma that occurred before the fire, and, if so, do the features contribute to the cause and manner of death? The beveled straight-edged fracture to the parietal was suspected to reflect characteristics of blunt trauma (Figure 14.22). With a closer examination and with comparable exemplar material, the parietal fragment does not appear to contribute to cause and manner of death. Several characteristics determined this:

- The texture and morphology of the beveled, sloping surface is undulating and is consistent with brittle, rather than viscoelastic, flaking (Figure 14.22).
- The internal fracture surface is scalloped and indicates brittle external cortical bone fire modification or flaking off as opposed to beveling due to bending, viscoelastic material (Figure 14.23). Unfortunately, this feature is not definitive enough to rule out trauma before the fire.

Fire and heat, however, are opportunistic and persistent: once soft tissues are destroyed, initial thermal damage to bone is always external. Certain areas of the skeleton, including

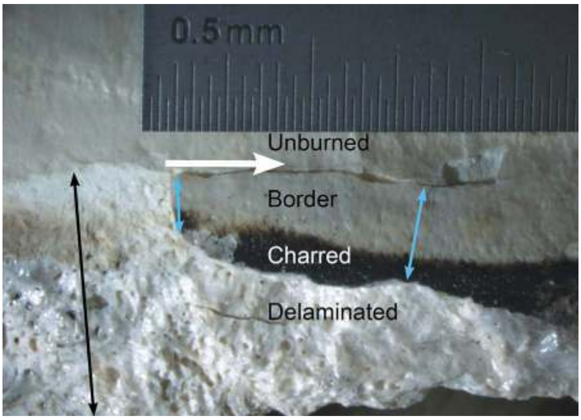

Figure 14.22 Fragment of the right parietal bone of the victim, Case Study 1; black arrows indicate a beveled surface.

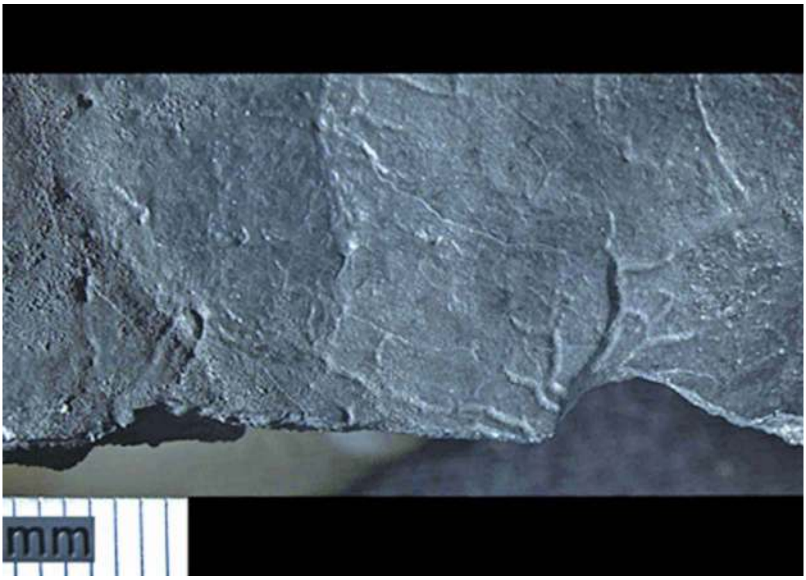

Figure 14.23 Fragment of the right parietal (internal) shows a scalloped fracture surface, indicating brittle external cortical bone fire modification or flaking off as opposed to beveling from bending a viscoelastic material (Case Study 1).

the skull, exhibit particular patterns of thermal destruction. The cranial vault has two layers of cortical bone separated by cancellous bone. If you combine this anatomical feature with the fact that external bone heats up first, the separation of external and internal layers (delamination) is inevitable. Even though the integrity of the internal skull is eventually compromised, the external skull continues to receive the brunt of the heat, so even with an open skull, beveling may occur with the gradient of temperatures. Closer examination of the parietal bone confirms beveling due to differential bone layer shrinkage as opposed to bending (compression, tension, and shear).

To confirm this pattern of delamination, an exemplar burned skull was examined and compared. Figure 14.24 is a closeup of that exemplar burned skull examined in a similar

Figure 14.24 Exemplar of the outer table of a burned parietal (unrelated to Case Study 1). The bone burns while fleshed or as the flesh recedes. Beveling can be observed between the black arrows. Above this area, more bone is in the process of further heat alteration and is shrinking, breaking, and creating beveling.

area of the cranial vault. The bevel is labeled with a black arrows, which is beneath the area that is cracked and about to delaminate. This example shows a gradient from unburned, to border, to carbonized, and eventually more beveled. Figure 14.25 shows in close-up the victim's right parietal fragment. Close examination reveals an identical pattern where the white arrow indicates the direction of failure of the cortical bone, and the encircled area is the cortical bone that is about to fail and flake off, leaving a longer beveled surface. If this

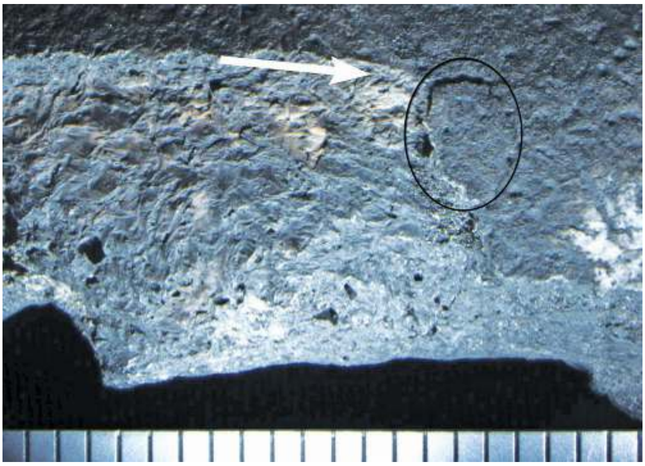

Figure 14.25 Close-up of the fragment of the right parietal of the victim, Case Study 1; black circle above the beveled area shows the progress of additional burn fractures.

had been a blunt impact to an unburned bone, there would not be the generation of flaking bone, and blunt trauma fractures would not be following thermal heat lines. Finally, the investigation recovered no skull fragments definitively indicative of blunt force or any other force for that matter. The separation of the inner and outer tables of cranial bone (Figure 14.8) is common in cases of thermal alteration (Symes et al. 2015). The fractured area in the parietal is no different and therefore appears to be fire-related. The fracture terminated in a way that indicated that the process of flaking would continue with further fire modification. In this case, the parietal fragment exhibits fracture characteristics associated with bone that rapidly dried and, due to heat shrinkage, fractured. The author (SAS) ascertained that the damage was consistent with a postmortem fracture.

This examination illustrates how a case referred to an anthropologist as a second opinion, produced, after many hours of the examination, no results that contributed to the cause of death. Despite the frustration of hours of examination for no immediately relevant results, this is a typical case for an anthropologist to confront. The analysis was not of a victim from 500 years ago, or even 50 years ago, but of a recent death, so repercussions of inaccuracy are severe. The evidence deserves an adequate investigation, examination, and interpretation. While the medical examiner and coroner must assess all situations of a recent death, anthropologists have no such obligation. Since this is a suspected homicide, there is no place for conjecture or hypothetical scenarios. An anthropologist's interpretation must stand up to scrutiny and accuracy in court and investigators. In this case, a suspicious bone was shown to be a product of burning, not a beating before the fire. These results, although mundane in appearance, are relevant and useful to the courts. This case, however, never went to trial due to an eventual guilty plea, which substantiates the original theories from investigators.

Case Study 2: Perimortem versus Postmortem in Thermal Modification

A forensic pathologist referred a case from the northernmost region of South Africa to an anthropologist for a second opinion on visible perimortem injury and associated heat fractures. A burned body of an adult had been discovered beneath rubble in an abandoned outdoor toilet. The body had been covered with a wheelbarrow and tires. Wires from the burnt tires were visible. Sharp force injuries from a knife were noted in the soft tissues of the neck, with an unusual burn pattern on the cranium. The anthropologist was requested to evaluate hard tissue from the skull and mandible. After processing and maceration of the cranium, a Zeiss stereo-microscope, Axio Zoom v.16, Plan Ap Z0.5x/0.125 FWD 114mm lenses, and an AxioCAMICc5 camera was used to analyze the bone. Macroscopic photographs were taken with an Olympus OMD-EM5ii.

A six-view of the burned cranium is shown in Figure 14.26 with the mandible in Figure 14.27. The burn pattern is both normal and abnormal when compared to cranial burn patterns associated with house and/or car fires (Figure 14.5; and "Pattern of Thermal Destructions" section, above). The right side of the cranium is carbonized and partially delaminated on the frontal, zygoma, and parietal regions with an absence of damage to the temporal area; this is consistent with exposure of a fleshed body to heat and flame. Similarly, the mandible also presents with a normal burn pattern with sparing of the well-protected bony ramus and mandibular condyles (Figure 14.27). In contrast to the normal patterns observed, abnormal carbonizing patterns were noted in the right nuchal region

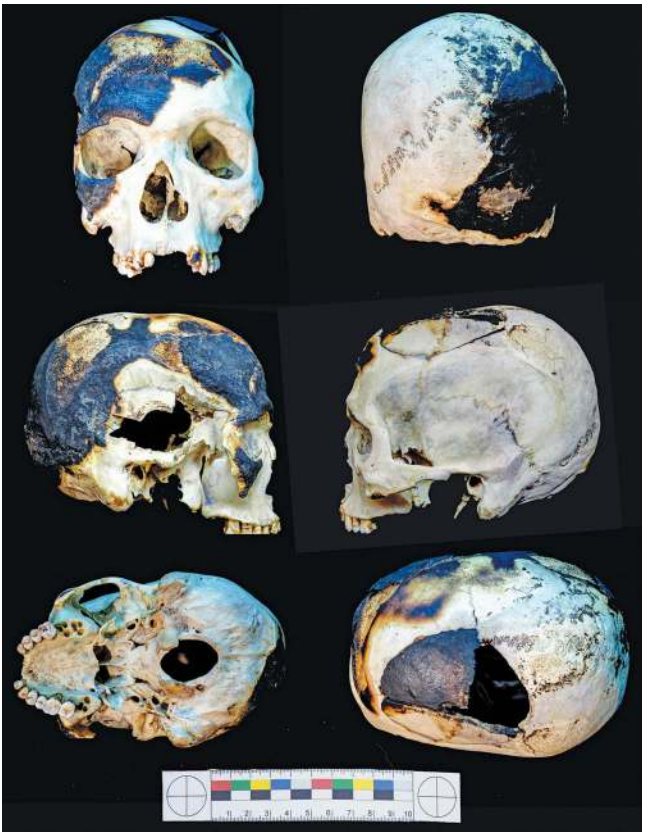

Figure 14.26 Six views of the cranium, Case Study 2. Note both a normal and abnormal burn pattern, likely due to the use of restraints (such as tires) and previous injury.

and base of the skull carbonized. In addition, the left side of the skull is unburned, indicating protection in this area. Protection was likely from the myriad of paraphernalia found with the body.

In the unburned area of the cranium, wet-bone injury was noted, namely the right temporal and the left fronto-parietal (Figures 14.28 and 14.29). No fractures, other than those associated with heat alterations, were observed in the mandible.

The right temporal bone is shown in Figure 14.28. Two radiating fractures are observed along with some debris and plastic deformation (red arrow) within the area of missing bone, indicating a *possible* impact site. One of the radiating fractures (blue arrow) travels anteriorly to the roof of the right orbit, where an unusual depressed and punctured-like defect was noted, also another *possible* impact site.

On the left middle image of Figure 14.29 (black arrows), a white heat line demarcates burned from unaltered bone on the skull. Adjacent to the white heat line and within the thermally altered border, longitudinal fractures and micro-fractures associated with dehydration and shrinking of bone from exposure to heat are observed. These radiating micro-fractures do not travel outside the burned area and therefore can be distinguished from fractures which occurred before the burn event. A radiating fracture (see white arrow), however, is noted running out of the carbonized area, suggesting that this fracture had occurred prior to burning.

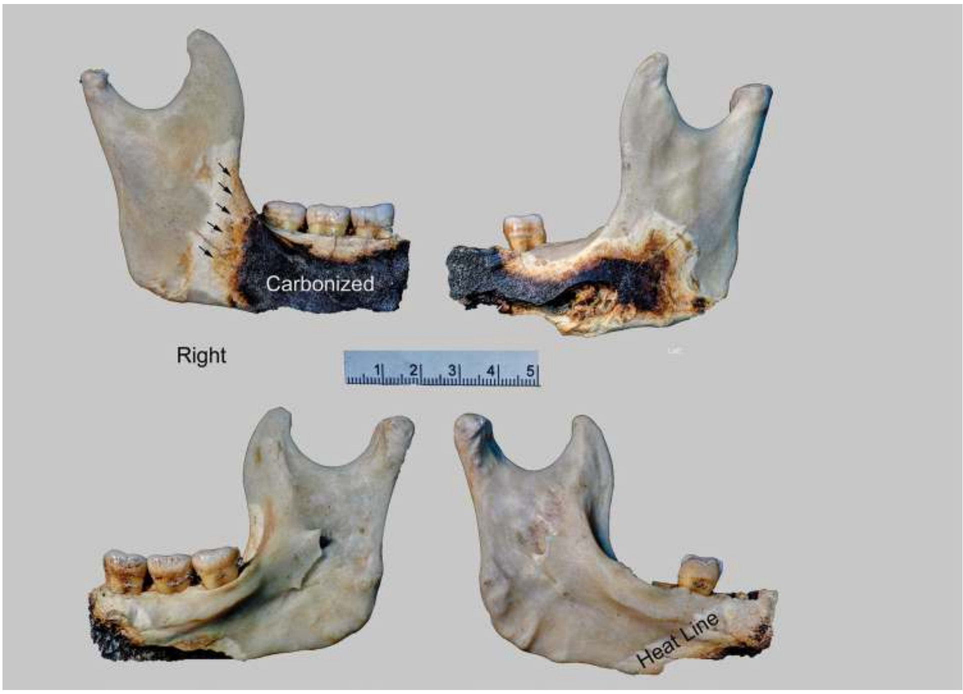

Figure 14.27 Normal burn pattern on the mandible with a visible white heat line, a heat-altered border (black arrows) and carbonized bone, Case Study 2.

The base of the zygomatic arch was broken and then burned (blue arrow, Figure 14.28), indicating that the damage had occurred before the burn event. No clear evidence of tensile or compressive stress failure could be seen on this portion of bone. A part of the temporal bone presented with plastic deformation and appears to be lifting up and off the cranium (red arrow, Figure 14.28). Similarly, external beveling, or angling of the bone, was noted on a fragment of the same temporal bone, also suggesting that the material had been lifted up and eventually failed. Other evidence of bone possibly lifting up and crushing into itself is noted just anterior to the temporal bone (black box in Figure 14.29). This pattern is inconsistent with bone being "pushed in" as would be expected in the cranium with a blunt force injury.

A defect on the left fronto-parietal bone is shown in Figure 14.30. Two fragments of bone are raised up from the defect, both fragments exhibit plastic deformation and appear to be "pushed out" from the cranium. The third fragment was missing, but external bevel was noted along the fracture edges (black arrow), indicating that the outer cortical bone layer was "pushed out". In addition, in the lower left corner of Figure 14.30, a white arrow is used to indicate a raised up and outwardly bent bone fragment. This bone fragment is used to highlight the outward bending direction of the bone. The burn pattern on the bone fragments is unusual, with one fragment having been completely carbonized, whereas the other fragment was hardly altered. As the one bone is likely to have been pushed out of the skull, the direct contact of the carbonized fragment to flame is highly probable.

While the right temporal area is *most likely* an impact site, a considerable amount of bone is missing such that the type of trauma, blunt, ballistic/projectile, or even sharp-blunt, cannot be clearly ascertained from this defect. While a cone beam computed tomography (CBCT) scan produced no observable lead on the inside of the cranium, this fact, alone,

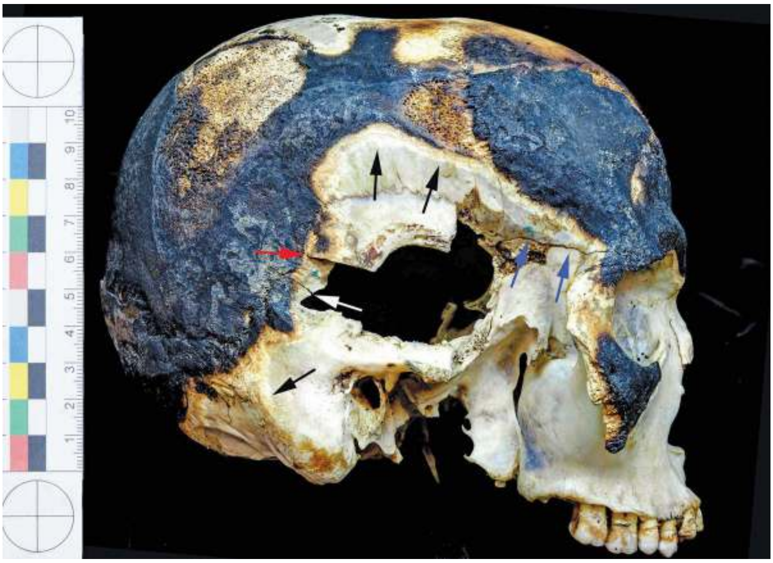

Figure 14.28 Right temporal bone area, Case Study 2. Two radiating fractures are observed along with some debris and plastic deformation (red arrow) within the area of missing bone, indicating a possible impact site. One of the radiating fractures (blue arrow) travels anteriorly to the roof of the right orbit, where an unusual depressed and punctured-like defect was noted, also another possible impact site. The white arrow highlights a radiating fracture running from the burned area. The black arrows indicate a white heat line.

cannot be used to exclude a ballistic/projectile injury. In examining Figures 14.27–14.29, a compressive force was applied to the bone such that the bone bent until it failed, which is supported with the observation of several radiating fractures (Figures 14.27 and 14.28). Once a bone has failed in a blunt force injury, further energy forces the fractured and segmented pieces to be pushed into the cranium and to bend, crush and finally tear, leaving

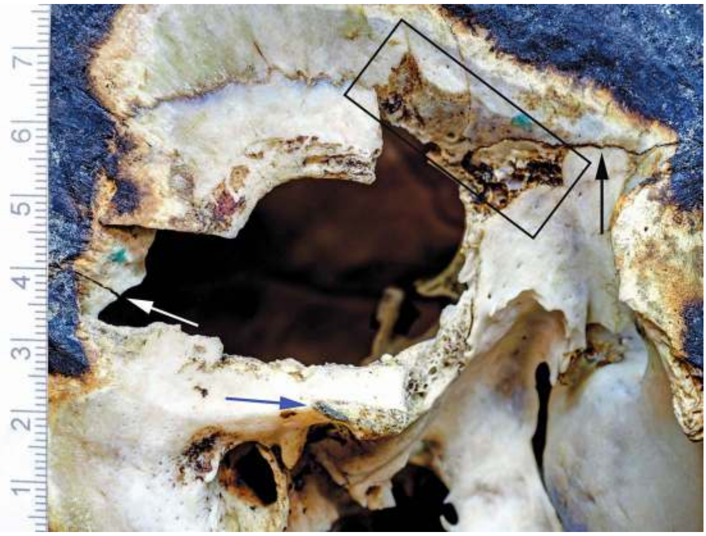

Figure 14.29 Right temporal bone area, Case Study 2. Evidence of perimortem injury is noted with a radiating fracture running from the burned area (white arrow) and plastic deformation (black square). Burning occurred to the zygomatic arch after a fracture to this region (blue arrow)

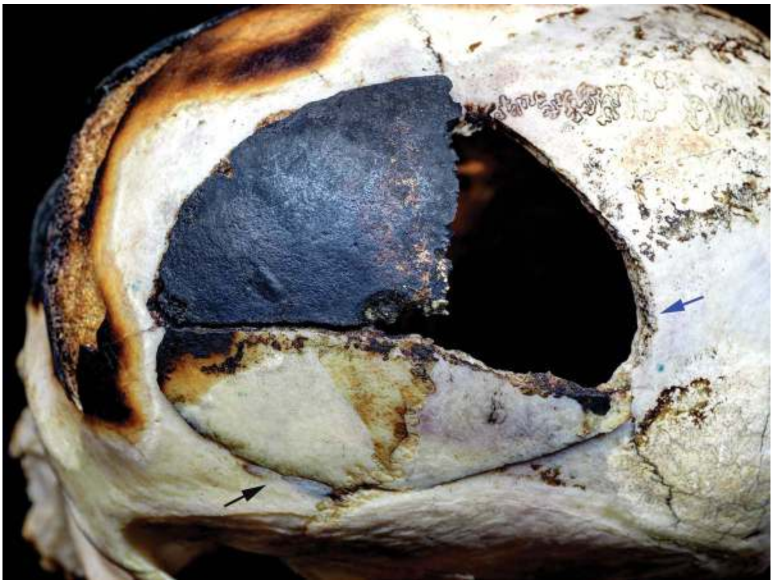

Figure 14.30 A defect on the left fronto-parietal bone, Case Study 2. Two fragments of bone are raised up from the defect, both fragments exhibit plastic deformation (black arrow) and appear to be "pushed out" (black and blue arrow) from the cranium.

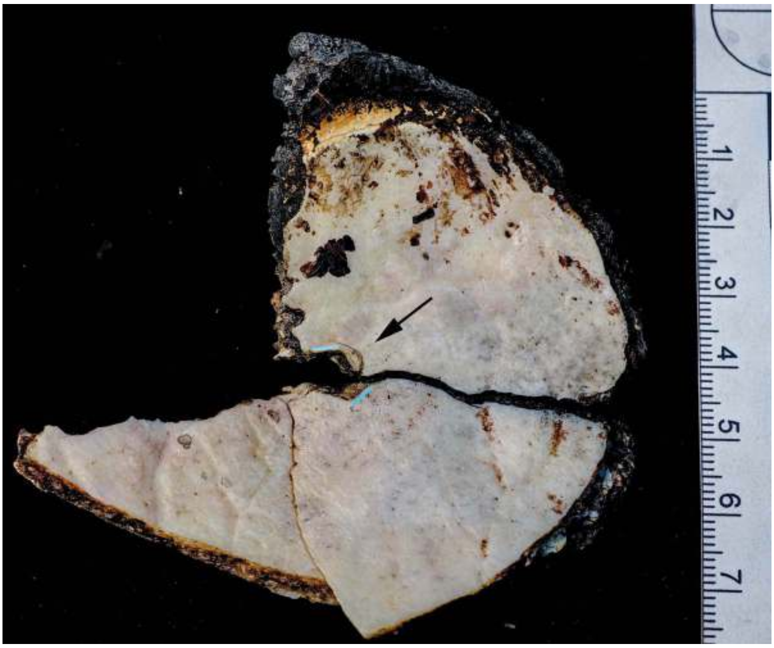

Figure 14.31 The edges of a possible tool mark are noted on the inner bone table with straight defects (black arrow and highlighted with blue borders), Case Study 2. This pattern is inconsistent with a bullet.

Figure 14.32 Close-up of the edges of a possible tool mark on the internal surface of the fronto-parietal bone (black arrow with the defect highlighted with blue lines), Case Study 2.

visible bone beveling on the surface which was under compressive stress (e.g., Symes et al. 2012). In this case, a blunt force fracture pattern was produced on the bone, but the force appears to be traveling from an internal to an external direction.

In Figures 14.31 and 14.32, the authors constructed blue lines around a small, narrowly focused area of punched out bone, with visible delamination and carbonization. The fracture pattern was quite irregular, where parts of the outer surface of bone are punched out, while parts of the inner surface are intact. In Figure 14.32, the internal surface of the three bone fragments are shown. On the internal surface, a section of the inner table of bone is clearly pushed out, as evidenced with bending of the bone, plastic deformation and a concentric fracture (note the black arrow in Figures 14.31 and 14.32). Also note the burning on the external and internal surface of one of the bone fragments, suggesting that this piece of bone, and possibly the other pieces, had been pushed out of the skull prior to the burn event.

The edges of a *possible* tool mark are noted on the inner bone table with straight defects (as highlighted with blue borders), a pattern which is inconsistent with a bullet (Figures 14.31 and 14.32). Likewise, the number of observed radiating fractures are few and, along with visible plastic deformation, can suggest a slow-loaded force, which is also inconsistent with high velocity trauma.

Summary

Many pieces of bone were missing from the right temporal and left parietal, creating difficulties in distinguishing not only the type of trauma that may have caused this injury but also the area of impact. A minimum of one defect was observed and is *possibly* penetrating blunt/sharp-blunt trauma. As the injury is on a curved surface and several fragments of bone are missing, no interpretations can be made about the area of impact, or even to clearly define the impact site. However, the left fronto-parietal bones were pushed out of the cranium, suggesting another area for an impact to have occurred. With the area of impact suggested to be in the right temporal region, the distance between the right temporal and left parietal was measured at 125 mm, which is consistent with the length of the blade removed from the soft tissues of the neck.

Conclusions

Thermal alteration of remains is a pervasive taphonomic process in forensic cases and may be associated with a cause of death, an immediate circumstance after death, multiple accidental scenarios, or a deliberate means to destroy evidence of a homicide victim's remains. Mayne Correia (1997) illustrated the 50-year debate and lack of consensus regarding the interpretation of burned skeletal remains. Interestingly enough, despite our observations and research, few issues have been concluded. This debate will continue.

Within complete cremations, various techniques can be used to estimate the biological profile (e.g., Grévin et al. 1998), interpret perimortem from postmortem burn injuries, and to distinguish human or nonhuman bone. According to Thompson (2004), the most influential variable with regard to heat-induced change is the removal of the organic components in bone and replacing/restricting them with inorganic material. This process affects the size, shape, and appearance of bone as well as its histological components (Bradtmiller and Buikstra 1984; Thompson 2005). Most importantly, the rapid dehydration, shrinking, and warping of burnt bone creates dry bone fractures superficially consistent with but more extreme than subaerial weathering (Chapter 11) that may obscure prior antemortem injuries.

In evaluating a burned body or burned skeletal elements, a forensic anthropologist needs to use knowledge of the pugilistic postural changes, biomechanics of burned bone, and fracture morphology to ascertain a normal or abnormal burn pattern, perimortem and postmortem bone injuries, and the possible condition of the body (fleshed or wet/dry) prior to the burn event. A forensic anthropologist, however, can only recognize perimortem burned trauma with insight into patterned thermal destruction to both soft tissue and bone. In addition, knowledge regarding the biomechanics of bone is necessary to distinguish perimortem fractures (impact site, bending of bone, and energy) and postmortem heat-induced damage (splitting of bone, cracking within burned areas but lacking energy to travel further than the burned area). Lastly, for an accurate analysis one also needs to have knowledge of the context in which the material was recovered (Dirkmaat et al. 2012). Anthropological "perimortem" may not focus as much on the death event itself, as much as simply describing the condition of bone, but it is the accurate analysis of the condition of bone that allows anthropologists to be forensic anthropologists. In Chapter 13, we advocate for the use of definitions such as wet and dry bone, instead of perimortem and postmortem.

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References

Adelson, L. (1955) Role of the pathologist in arson investigation. *The Journal of Criminal Law, Criminology, and Police Science* 45(6):760–768.

Alunni, V., L. Nogueira, and G. Quatrehomme (2017) Macroscopic and stereomicroscopic comparison of hacking trauma of bones before and after carbonization. *International Journal of Legal Medicine* 132(2):643–648.

Baby, R. S. (1954) Hopewell cremation practices. *The Ohio Historical Society Papers in Archaeology* 1:1–7.

Baker, A. J. (2004) *A Taphonomic Analysis of Human Cremains from the Fox Hollow Farm Serial Homicide Site*. M.A. Thesis, University of Indianapolis, Indianapolis, IN.

Bass, W. M. (1984) Is it possible to consume a body completely in a fire? In *Human Identification: Case Studies in Forensic Anthropology* ed. by T. Rathbun and J. Buikstra, pp. 159–167. Charles C Thomas, Springfield, IL.

Bass, W. M. and R. L. Jantz (2004) Cremation weights in east Tennessee. *Journal of Forensic Sciences* 49(5):901–904.

Beach, J. J., N. V. Passalacqua, and E. N. Chapman (2008) Tooth color: Temperature versus duration of exposure. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 137–144. Academic Press, Amsterdam.

Behrensmeyer, A. K. (1978). Taphonomic and ecologic information from bone weathering. *Paleobiology* 4(2):150–162.

Binford, L. R. (1963) An analysis of cremations from three Michigan sites. *Wisconsin Archaeologist* 44(2):98–110.

Binford, L. R. (1972) *An Archaeological Perspective*. Seminar Press, New York.

Bohnert, M., T. Rost, and S. Pollak (1998) The degree of destruction of human bodies in relation to the duration of the fire. *Forensic Science International* 95(1):11–21.

Bonucci, E., and G. Graziani (1975). Comparative thermogravimetric, X-ray diffraction and electron microscope investigations of burnt bones from recent, ancient, and prehistoric age. *Atti Memorie Accademia Nazionale die Lincei Scienze, Fisiche, Matematiche Naturali Series* 8(59):517–534.

Bornman, E., R. van Eeden, and M. Wentzel (eds.) (1998) *Violence in South Africa: A Variety of Perspectives*. Human Sciences Research Council, Pretoria.

Bosch, P., I. Alemán, C. Moreno-Castilla, and M. Botella (2011) Boiled versus unboiled: A study on Neolithic and contemporary human bones. *Journal of Archaeological Science* 38(10): 2561–2570.

Bradtmiller, B. and J. E. Buikstra (1984) The effects of burning on human bone microstructure: A preliminary study. *Journal of Forensic Sciences* 29(2):535–540.

Brits, D., M. Steyn, and E. N. L'Abbé (2014) A histomorphological analysis of human and nonhuman femora. *International Journal of Legal Medicine* 128(2): 369–377.

Brooks, T. R., T. E. Bodkin, G. E. Potts, and S. A. Smullen (2006) Elemental analysis of human cremains using ICP-OES to classify legitimate and contaminated cremains. *Journal of Forensic Sciences* 51(5):967–973.

Buikstra, J. E., and D. H. Ubelaker (eds.) (1994) *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archeological Survey Research Series No. 44, Fayetteville, AR.

Buikstra, J., and M. Swegle (1989) Bone modification due to burning: Experimental evidence. In *Bone Modification* ed. by R. Bonnichsen and M. H. Sorg, pp. 247–258. Center for Study of the First Americans, Orono, ME.

Campbell, M. N., and S. I. Fairgrieve (2011) Differentiation of traumatic and heat-induced dental tissue fractures via SEM analysis. *Journal of Forensic Sciences* 56(3):715–719.

Cheney, N. P., J. S. Gould, W. L. McCaw, and W. R. Anderson (2012) Predicting fire behavior in dry eucalyptus forest in southern Australia. *Forest Ecology and Management* 280:120–131.

Cremation Association of North America (2019) History of Cremation. Electronic document, https://www.cremationassociation.org/page/HistoryOfCremation, accessed 14 February 2021.

Currey, J. D. (2002) *Bones: Structure and Mechanics* (2nd ed.). Princeton University Press, Princeton, NJ.

Curtin, A. J. (2008) Putting together the pieces: Reconstructing mortuary practices from commingled ossuary cremains. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 201–209. Academic Press, Amsterdam.

Davies, D. J., and L. H. Mates (eds.) (2005) *The Encyclopedia of Cremation*. Ashgate, Aldershot, UK.

De Angelis, D., F. Collini, E. Muccino, A. Cappella, E. Sguazza, A. Mazzucchi, and C. Cattaneo (2017) Analysis of metallic medical devices after cremation: The importance in identification. *Science & Justice* 57(2):128–135.

de Gruchy, S., and T. L. Rogers (2002) Identifying chop marks on cremated bone: A preliminary study. *Journal of Forensic Sciences* 47(5):933–936.

Degusta, D. (2000) Fijian cannibalism and mortuary ritual: Bioarchaeological evidence from Vunda. *International Journal of Osteoarchaeology* 10(1):76–92.

DeHaan, J. D. (2008) Fire and bodies. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 1–13. Academic Press, Amsterdam.

DeHaan, J. D. (2012) Sustained combustion of bodies: Some observations. *Journal of Forensic Sciences* 57(6):1578–1584.

Devlin, J. B., and N. P. Herrmann (2008) Bone color as an interpretive tool of the depositional history of archaeological cremains. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 109–128. Academic Press, Amsterdam.

Dirkmaat, D. C., G. O. Olson, A. R. Klales, and S. Getz (2012) The role of forensic anthropology in the recovery and interpretation of the fatal-fire victim. In *A Companion to Forensic Anthropology* ed. by D. C. Dirkmaat, pp. 113–135. Wiley-Blackwell, Chichester, UK.

Dunlop, J. (1978) Traffic light discoloration in cremated bones. *Medicine, Science and the Law* 18(3):163–173.

Ellingham, S. T. D., T. J. U. Thompson, and M. Islam (2015) Thermogravimetric analysis of property changes and weight loss in incinerated bone. *Palaeogeography, Palaeoclimatology Palaeoecology* 438:239–244.

Etxeberria, F. (1994) Aspectos macroscópicos del hueso sometido al fuego: Revisión de las cremaciones descritas en el País Vasco desde la arqueología. *Munibe* 46:111–116.

Fairgrieve, S. I. (2008) *Forensic Cremation: Recovery and Analysis*. CRC Press, Boca Raton, FL.

Fenton, T. W., W. H. Birkby, and J. Cornelison (2003) A fast and safe non-bleaching method for forensic skeletal preparation. *Journal of Forensic Sciences* 48(1):274–276.

Flinn, L., C. G. Turner, and A. Brew (1976) Additional evidence for cannibalism in the Southwest: The case of LA 4528. *American Antiquity* 41:308–318.

Fojas, C., C. W. Rainwater, and S. A. Symes (2011) Using spatial analysis to recognize normal and abnormal patterns in burned bodies. *Proceedings of the American Academy of Forensic Sciences* 17:367–368.

Galtés, I., and S. Scheirs (2019) Differentiation between perimortem trauma and heat induced-damage: The use of perimortem traits on blunt long bones. *Forensic Science, Medicine and Pathology* 15(3):453–457.

Gilchrist, M., and H. Mytum (1986) Experimental archaeology and burnt animal bone from archaeological sites. *Circaea* 4(1):29–38.

Glassman, R. M., and D. M. Crow (1996) Standardization model for describing the extent of burn injury to human remains. *Journal of Forensic Sciences* 41(1):152–154.

Godinho, R. M., I. Oliveira-Santos, A. Maurício, A. Valera, and D. Gonçalves (2019) Is enamel the only reliable hard tissue for sex metric estimation of burned skeletal remains in biological anthropology? *Journal of Archaeological Science: Reports* 26:101876.

Gonçalves, D., E. Cunha, and T. J. U Thompson (2015). Estimation of the pre-burning condition of human remains in forensic contexts. *International Journal of Legal Medicine* 129(5): 1137-1143.

Gonçalves, D., E. Cunha, and T. J. U. Thompson (2013) Weight references for burned human skeletal remains from Portuguese samples. *Journal of Forensic Sciences* 58(5):1134–1140.

Gonçalves, D., T. J. U. Thompson, and E. Cunha (2011) Implication of heat-induced changes in bone on the interpretation of funerary behavior and practice. *Journal of Archaeological Science* 38(6):1308–1313.

Gough, M. A., J. T. Pokines, and S. Botch-Jones (2021) Experimental study of white heat line formation in burned bone using Fourier Transform Infrared Spectroscopy. *Forensic Anthropology*. DOI: 10.5744/fa.2020.0038.

Gouveia, M. F., I. O. Santos, A. L. Santos, and D. Gonçalves (2017) Sample-specific odontometric sex estimation: A method with potential application to burned remains. *Science & Justice* 57(4):262–269.

Graver, S., K. D. Sobolik, and J. Whittaker (2002) Cannibalism or violent death alone? Human remains at a small Anasazi site. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 309–320. CRC Press, Boca Raton, FL.

Grévin, G., P. Bailet, G. Quatrehomme, and A. Ollier (1998) Anatomical reconstruction of fragments of burned human bones: A necessary means for forensic identification. *Forensic Science International* 96(2-3):129–134.

Grupe, G., and S. Hummel (1991) Trace element studies on experimentally cremated bone. I. Alteration of the chemical composition at high temperatures. *Journal of Archaeological Science* 18(2):177–186.

Haglund, W. D., and M. H. Sorg (eds.) (1997) *Forensic Taphonomy: The Postmortem Fate of Human Remains*. CRC Press, Boca Raton, FL.

Haglund, W. D., and M. H. Sorg (eds.) (2002) *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives*. CRC Press, Boca Raton, FL.

Hansen, K. (2012) Choosing to be flushed away: A national background on alkaline hydrolysis and what Texas should know about regulating liquid cremation. *Estate Planning and Community Property Law Journal* 5:145–170.

Heglar, R. (1984) Burned remains. In *Human Identification: Case Studies in Forensic Anthropology* ed. by T. Rathbun and J. E. Buikstra, pp. 148–158. Charles C Thomas, Springfield, IL.

Herrmann, N. P., and J. L. Bennett (1999) The differentiation of traumatic and heat-related fractures in burned bone. *Journal of Forensic Sciences* 44(3):461–469.

Hiller, J. T., J. U. Thompson, M. P. Evison, A. T. Chamberlain, and T. J. Weiss (2003) Bone mineral change during experimental heating: An X-ray scattering investigation. *Biomaterials* 24(28):5091–5097.

Hillier, M. L., and L. S. Bell (2007) Differentiating human bone from animal bone: A review of histological methods. *Journal of Forensic Sciences* 52(2):249–263.

Hughes, C. E., and C. A. White (2009) Crack propagation in teeth: A comparison of perimortem and postmortem behavior of dental materials and cracks. *Journal of Forensic Sciences* 54(2):263–266.

Hurlbut, S. A. (2000) The taphonomy of cannibalism: A review of anthropogenic bone modification in the American Southwest. *International Journal of Osteoarchaeology* 10(1):4–26.

Icove, D. J., and J. D. DeHaan (2003) *Forensic Fire Scene Reconstruction*. Prentice Hall, New York.

Kennedy, K. A. R. (1996) The wrong urn: Commingling of cremains in mortuary practices. *Journal of Forensic Sciences* 41(4):689–692.

Keough, N. (2013) *Skeletal Changes after Post-Mortem Exposure to Fire as an Indicator of Decomposition Stage*. Ph.D. dissertation, University of Pretoria.

Keough, N., E. N. L'Abbé, M. Steyn, and S. Pretorius (2015) Assessment of skeletal changes after post-mortem exposure to fire as an indicator of decomposition stage. *Forensic Science International* 246:17–24.

Keough, N., K. Colman, E. N. L'Abbé, S. A. Symes, and L. Cabo (2012) Distinguishing features of thermal destruction on fleshed, wet and dry remains. *Proceedings of the American Academy of Forensic Sciences* 18:386.

Koon, H. E. C., T. P. O'Connor, and M. J. Collins (2010) Sorting the butchered from the boiled. *Journal of Archaeological Science* 37(1):62–69.

Krap, T., K. Nota, L. S. Wilk, F. R. van de Goot, J. M. Ruijter, W. Duijst, and R. J. Oostra (2017) Luminescence of thermally altered human skeletal remains. *International Journal of Legal Medicine* 131(4):1165–1177.

Krogman, W. M. (1943a) Role of the physical anthropologist in the identification of human skeletal remains, Part I. *FBI Law Enforcement Bulletin* 12(4):17–40.

Krogman, W. M. (1943b) Role of the physical anthropologist in the identification of human skeletal remains, Part II. *FBI Law Enforcement Bulletin* 12(5):12–28.

L'Abbé, E. N., S. A. Symes, J. T. Pokines, L. L. Cabo, K. E. Stull, S. Kuo, D. E. Raymond, P. S. Randolph-Quinney, and L. R. Berger (2015) Evidence of fatal skeletal injuries on Malapa Hominins 1 and 2. *Scientific Reports* 5(1):1–11.

Liebenberg, M. (2020) *The Effects of Bone Condition and Fire Duration on Standard Anthropological Measurements Using Pigs as an Animal Model*. M.Sc. Thesis, University of Pretoria.

López-González, F., A. Grandal-d'Anglade, and J. R. Vidal-Romaní (2006) Deciphering bone depositional sequences in caves through the study of manganese coatings. *Journal of Archaeological Science* 33(5):707–717.

Lupo, K. D., and D. N. Schmitt (1997) Experiments in bone boiling: Nutritional returns and archaeological reflections. *Anthropozoologica* 25–26:137–144.

Macoveciuc, I., N. Márquez-Grant, I. Horsfall, and P. Zioupos (2017) Sharp and blunt force trauma concealment by thermal alteration in homicides: An in-vitro experiment for methodology and protocol development in forensic anthropological analysis of burnt bones. *Forensic Science International* 275:260–271.

Marciniak, S. M. (2009) A preliminary assessment of the identification of saw marks on burned bone. *Journal of Forensic Sciences* 54(4):779–785.

Marín Arroyo, A. B., M. D. Landete Ruiz, G. Vidal Bernabeu, R. Seva Román, M. R. González Morales, and L. G. Straus (2008) Archaeological implications of human-derived manganese coatings: A study of blackened bones in El Mirón Cave, Cantabrian Spain. *Journal of Archaeological Science* 35(3):801–813.

Mayne Correia, P. M. (1997) Fire modification of bone: A review of the literature. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 275–293. CRC Press, Boca Raton, FL.

Mayne Correia, P. M., and O. Beattie (2002) A critical look at methods for recovering, evaluating, and interpreting cremated human remains. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 435–450. CRC Press, Boca Raton, FL.

Mays, S. (2008). Metabolic bone disease. In *Advances in Human Palaeopathology* ed. by R. Pinhasi and S. Mays, pp. 215–252. John Wiley & Sons, Chichester, UK.

Mincer, H. H., H. E. Berryman, G. A. Murray, and R. L. Dickens (1990) Methods for physical stabilization of ashed teeth in incinerated remains. *Journal of Forensic Sciences* 35(4):971–974.

Moore-Jansen, P. H., and R. L. Jantz (1994) *Data Collection Procedures for Forensic Skeletal Material*. Forensic Anthropology Center, University of Tennessee, Knoxville, TN.

Murray, K. A., and J. C. Rose (1993) The analysis of cremains: A case study involving the inappropriate disposal of mortuary remains. *Journal of Forensic Sciences* 38(1):98–103.

Nawrocki, S. P. (2009) Forensic taphonomy. In *Handbook of Forensic Anthropology and Archaeology* ed. S. Blau and D. H. Ubelaker, pp. 284–294. Left Coast Press, Walnut Creek, CA.

Oliveira-Santos, I., M. Gouveia, E. Cunha, and D. Gonçalves (2017) The circles of life: Age at death estimation in burnt teeth through tooth cementum annulations. *International Journal of Legal Medicine* 131(2):527–536.

Ortner, D. J. (2008) Differential diagnosis of skeletal lesions in infectious disease. In *Advances in Human Palaeopathology* ed. by R. Pinhasi and S. Mays, pp. 191–214. John Wiley & Sons, Chichester, UK.

Owsley, D. W. (1993) Identification of the fragmentary, burned remains of two U.S. journalists seven years after their disappearance in Guatemala. *Journal of Forensic Sciences* 38(6):1372–1382.

Owsley, D. W., R. W. Mann, R. E. Chapman, E. Moore, and W. A. Cox (1993) Positive identification in a case of intentional extreme fragmentation. *Journal of Forensic Sciences* 38(4):985–996.

Piepenbrink, H. (1986) Two examples of biogenous dead bone decomposition and their consequences for taphonomic interpretation. *Journal of Archaeological Science* 13(5):417–430.

Pope, E. J. (2007) *The Effects of Fire on Human Remains: Characteristics of Taphonomy and Trauma*. Ph.D. Dissertation, University of Arkansas, Fayetteville, AR.

Pope, E. J., and O'B. C. Smith (2004) Identification of traumatic injury in burned cranial bone: An experimental approach. *Journal of Forensic Sciences* 49(3):431–440.

Pope, E. J., C. A. Juarez, and A. Galloway (2021) A redefined classification system for thermally altered damaged human remains by body segment. *Proceedings of the American Academy of Forensic Sciences* 27:127.

Powell, D. (2017) Dissolve the Dead? Controversy Swirls Around Liquid Cremation. Electronic document, http://www.scientificamerican.com/article/dissolve-the-dead-controversy-swirls-around-liquid-cremation, accessed 14 February 2021.

Reilly, D. T., and A. H. Burstein (1974) The mechanical properties of cortical bone. *Journal of Bone and Joint Surgery* 56A(5):1001–1022.

Rennick, S. L., T. W. Fenton, and D. R. Foran (2005) The effects of skeletal preparation techniques on DNA from human and non-human bone. *Journal of Forensic Sciences* 50(5):1016–1019.

Roberts, S. J., C. I. Smith, A. Millard, and M. J. Collins (2002) The taphonomy of cooked bone: Characterizing boiling and its physico-chemical effects. *Archaeometry* 44(3):485–494.

Rosen, F. (2004) *Cremation in America*. Prometheus Books, Amherst, NY.

Sandholzer, M. A., K. Baron, P. Heimel, and B. D. Metscher (2014) Volume analysis of heat-induced cracks in human molars: A preliminary study. *Journal of Forensic Dental Sciences* 6(2):139–144.

Sandholzer, M. A., A. D. Walmsley, P. J. Lumley, and G. Landini (2013) Radiologic evaluation of heat-induced shrinkage and shape preservation of human teeth using micro-CT. *Journal of Forensic Radiology and Imaging* 1(3):107–111.

Schmidt, C. W. (2008) The recovery and study of burned human teeth. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 55–74. Academic Press, Amsterdam.

Schultz, J. J., M. W. Warren, and J. S. Krigbaum (2008) Analysis of human cremains: Gross and chemical methods. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 75–94. Academic Press, Amsterdam.

Schwark T., A. Heinrich, A. Preuße-Prange, and N. von Wurmb-Schwark (2011) Reliable genetic identification of burnt human remains. *Forensic Science International: Genetics* 5(5):393–399.

Shahack-Gross, R. O. Bar-Yosef, and S. Weiner (1997) Black-colored bones in Hayonim Cave, Israel: Differentiating between burning and oxide staining. *Journal of Archaeological Science* 24(5):439–446.

Shipman, P., G. Foster, and M. Schoeninger (1984) Burnt bones and teeth: An experimental study of color, morphology, crystal structure and shrinkage. *Journal of Archaeological Science* 11(4):307–325.

Spitz, W. U. (1993) Thermal injuries. In *Spitz and Fisher's Medicolegal Investigation of Death: Guidelines for the Application of Pathology to Crime Investigation* (3rd ed.) ed. by W. U. Spitz, pp. 413–443. Charles C Thomas, Springfield, IL.

Stephens, S. L. B. M. Collins, C. J. Fettig, M. A. Finney, C. M. Hoffman, E. E. Knapp, M. P. North, H. Safford, and R. B. Wayman (2018) Drought, tree mortality, and wildfire in forests adapted to frequent fire. *BioScience* 68(2):77–88.

Stiner, M. C., S. L. Kuhn, and O. Bar-Yosef (1995) Differential burning, recrystallization, and fragmentation of archaeological bone. *Journal of Archaeological Science* 22(2):223–237.

Symes S. A., E. N. L'Abbé, E. N. Chapman, I. Wolff, and D. C. Dirkmaat (2012) Interpreting traumatic injury from bone in medico-legal investigations. In *Companion to Forensic Anthropology* ed. by D. C. Dirkmaat, pp. 340–389. Wiley-Blackwell, London.

Symes, S. A., A. M. Kroman, C. W. Rainwater, and A. L. Piper (2005) Bone biomechanical considerations in perimortem vs. postmortem thermal bone fractures: Fracture analyses on victims of suspicious fire scenes. Poster presented at the *104th Annual Meeting of the American Association of Physical Anthropology*, 8 April 2005, Milwaukee, WI.

Symes, S. A., C. W. Rainwater, E. N. Chapman, D. R. Gipson, and A. L. Piper (2015) Patterned thermal destruction of human remains in a forensic setting. In *The Analysis of Burned Human Remains* (2nd ed.) ed. by C. W. Schmidt and S. A. Symes, pp. 17–59. Academic Press, Amsterdam.

Symes, S. A., E. J. Pope, O. C. Smith, C. D. Gardner, and L. A. Zephro (2001) Burning observations III: Analysis of fracture patterns in burned human remains. *Proceedings of the American Academy of Forensic Sciences* 7:278.

Symes, S. A., O'B. C. Smith, H. Berryman, and E. J. Pope (1999) Patterned thermal destruction of human remains. Paper presented to the *30th Anniversary of the T. D. Stewart Personal Identification in Mass Disasters*, Central Identification Laboratory, Honolulu, Hawaii.

Thompson, T. J. U. (2004) Recent advances in the study of burned bone and their implications for forensic anthropology. *Forensic Science International* 146:203–205.

Thompson, T. J. U. (2005) Heat-induced dimensional changes in bone and their consequences for forensic anthropology. *Journal of Forensic Sciences* 50(5):1008–1015.

Thurman, M., and L. J. Willmore (1980-81) A replicative cremation experiment. *North American Archaeologist* 2(4):275–283.

Trotter, M., and R. R. Peterson (1955) Ash weight of human skeletons in per cent of their dry, fat-free weight. *The Anatomical Record* 123:341–358.

Trujillo-Mederos, A., I. Alemán, M. Botella, and P. Bosch (2012) Changes in human bones boiled in seawater. *Journal of Archaeological Science* 39(4):1072–1079.

Turner, C. G., and J. A. Turner (1992) The first claim for cannibalism in the Southwest: Walter Hough's 1901 discovery at Canyon Butte Ruin 3, Northeastern Arizona. *American Antiquity* 57:661–682.

Turner, C. G., and J. A. Turner (1999) *Man Corn: Cannibalism and Violence in the Prehistoric American Southwest*. University of Utah Press, Salt Lake City, UT.

U.S. Cremation Equipment (2019) Products. Electronic document, https://uscremationequipment.com/products/, accessed 21 February 2021.

Ubelaker, D. H., and B. J. Adams (1995) Differentiation of perimortem and postmortem trauma using taphonomic indicators. *Journal of Forensic Sciences* 40(3):509–512.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–90. CRC Press, Boca Raton, FL.

Ubelaker, D. H. (2009) The forensic evaluation of burned skeletal remains: A synthesis. *Forensic Science International* 183(1-3):1–5.

Ubelaker, D. H., and C. H. Jacobs (1995) Identification of orthopedic device manufacturer. *Journal of Forensic Sciences* 40(2):168–170.

Ubelaker, D. H., D. W. Owsley, M. M. Houck, E. Craig, W. Grant, T. Woltanski, R. Fram, K. Sandness, and N. Peerwani (1995) The role of forensic anthropology in the recovery and analysis of Branch Davidian compound victims: Recovery procedures and characteristics of the victims. *Journal of Forensic Sciences* 40(3):335–340.

Van Deest, T. L., T. A. Murad, and E. J. Bartelink (2011) A re-examination of cremains weight: Sex and age variation in a Northern California sample. *Journal of Forensic Sciences* 56(2):344–349.

VanDeest, T. L., M. W. Warren, and K. L. Bolhofner (2012) Advances in the anthropological analysis of cremated remains. In *Companion to Forensic Anthropology* ed. by D. C. Dirkmaat, pp. 418–431. Wiley-Blackwell, London.

Walker, P. L., and K. P. Miller (2005) Time, temperature, and oxygen availability: An experimental study of the effects of environmental conditions on the color and organic content of cremated bone. Poster presented at the *104th Annual Meeting of the American Association of Physical Anthropologists*, 8 April 2005, Milwaukee, WI.

Walker, P. L., K. W. P. Miller, and R. Richman (2008) Time, temperature, and oxygen availability: An experimental study of the effects of environmental conditions on the color and organic content of cremated bone. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 129–135. Academic Press, Amsterdam.

Warren, M. W., and J. J. Schultz (2002) Post-cremation taphonomy and artifact preservation. *Journal of Forensic Sciences* 47(3):656–659.

Warren, M. W., and W. R. Maples (1997) The anthropometry of contemporary commercial cremation. *Journal of Forensic Sciences* 42(3):417–423.

White, T. D. (1992) *Prehistoric Cannibalism at Mancos 5Mtumr-2346*. Princeton University Press, Princeton, NJ.

Whyte, T. R. (2001) Distinguishing remains of human cremations from burned animal bones. *Journal of Field Archaeology* 28(3–4):437–448.

Williams, A. N. (2020) *A New Classification System for Analyzing Burned Human Remains*. Ph.D. Dissertation, University of Montana, Missoula, MT.

DNA Survivability in Skeletal Remains

15

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Contents

> There's no gene for fate.
>
> **—Vincent Freeman**
> *Gattaca*

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Introduction

The analysis of DNA from skeletal remains has numerous applications in archaeological and forensic contexts. In archaeological settings, bones and teeth represent the most numerous human biological materials to survive from the past, and morphological or genetic analyses of these hard tissues can provide invaluable insight into deceased individuals and past populations. In a forensic context, identification may be difficult once all soft tissues have decomposed beyond recognition, and the analysis of skeletal remains is often the only means to gather forensically significant information long after the death of the individual.

Bones encountered by the analyst will vary in their degree of degradation, as will the condition of the DNA contained within the hard tissues. The low copy numbers of template DNA and the DNA modifications accrued during the decomposition process can potentially pose complications for subsequent genetic analyses. Progress has been made, however, in the specific analytical techniques employed when analyzing DNA isolated from skeletal remains when more optimal DNA samples are not available for investigation. In addition, certain genetic loci have been shown to be more useful in terms of analysis when working with skeletal DNA. It is important not only to recognize such possible difficulties, but also to have a basic understanding of what is happening to the DNA contained within the human body after cell death.

DNA and Human Identification

Genetic analysis has established itself as a fundamental tool in the positive identification of human skeletal remains. The various genetic techniques employed in positive identification involve the comparison of a DNA profile obtained from unidentified remains to a DNA profile known to have originated from the missing person or close relative. Current techniques rely upon the ability to make many copies of the regions of the genome analyzed for identification purposes using a process called *polymerase chain reaction* (PCR). The PCR process is essentially a “molecular copy machine” that enables analysts to produce sufficient copies of the DNA region of interest to be detected and analyzed.

PCR employs enzymes (*DNA polymerases*) that selectively amplify a DNA segment delineated by synthetically produced single-stranded DNA primers (*synthetic oligonucleotide primers*). The target DNA is heated to denature the double-stranded molecule into single strands and then cooled to allow the single-stranded primers to hybridize to complementary regions in the genome defining the region of interest. The enzymes then construct complimentary copies of the target DNA by incorporating free nucleotides (*deoxynucleotide triphosphates*) into a newly constructed DNA molecule. This process is repeated until millions of copies (*amplicons*) of the original target DNA are produced.

An advantage of PCR-based genetic analysis is that it is often sensitive enough to replicate the suboptimal, low quantity, and degraded DNA samples recovered from skeletonized remains in order to produce a genetic profile. Current technologies allow for the generation of DNA profiles from samples containing 100 picograms (pg) or less of template DNA (Elwick et al. 2018; Ensenberger et al. 2016; Oostdik et al. 2014). This process is referred to as *low copy number* (LCN) DNA testing. Research has shown, however, that interpretations from LCN samples should be approached with caution, because the increased sensitivity used for the generation of LCN profiles also allows for the detection of low levels of contaminant DNA (Alonso et al. 2004; Cale et al. 2016; Davoren et al. 2007; Gill et al. 2000).

While the PCR process is essential for genetic analyses, it also has its limitations. PCR requires that the DNA be sufficiently preserved to serve as a template for the DNA polymerases. If the enzymes encounter lesions or other modifications of the template DNA, they are unable to continue copying the DNA molecule. Unlike the process of DNA replication in the human body, PCR does not have proofreading abilities, so analysts must be cautious as to the possibility of misincorporated bases. This is especially problematic if the template DNA is damaged or degraded. In addition, the DNA sample must be free of co-purified substances that act as inhibitors to the PCR process (Amory et al. 2012; Davoren et al. 2007; Edson 2019c; Geigl 2002; Hagelberg et al. 1991; Kalmár et al. 2000; Lee et al. 2009; Rogan and Salvo 1990).

The human genome consists of *nuclear DNA* (nucDNA) and *mitochondrial DNA* (mtDNA). The human nuclear genome is most often employed in forensic investigations and is comprised of approximately six billion base pairs (bp) per diploid cell. Forensic genetic analyses rely on regions of the genome that are highly polymorphic within the population at large. Employing loci that exhibit a wide range of variability across the human population increases the probability that the genetic profiles generated from two unrelated individuals will be different and therefore individualizing. For identification purposes, this allows for two samples to be compared and either exclusions be made if the DNA profiles do not match or statistical probabilities of a match be calculated if the two DNA profiles are consistent.

Nuclear DNA

Nuclear DNA is wrapped around proteins to form chromatin, which is packaged into chromosome structures contained within the cell nucleus. The 46 human chromosomes are arranged into 22 homologous pairs (*autosomal chromosomes*) and one pair of sex chromosomes, from which individuals inherit one copy of one half of the pair from their mother and one copy of one half of the pair from their father, creating a biparental inheritance pattern. Thus, nucDNA is a representation of an individual's ancestors' DNA. Genetic recombination between the homologous chromosomes creates a situation where the DNA is continually mixed and shuffled from generation to generation, and this inheritance pattern produces a unique genetic profile for each individual (except, in most cases, identical twins).

The loci most commonly utilized in forensic genetic analyses are *nuclear short tandem repeats* (STRs), which are DNA sequences comprised of tandem repeats with a core repeating unit of two to six nucleotides. STRs are noncoding regions of the genome, meaning they do not code for proteins that contribute to the body's phenotype. Of these, the tetranucleotide repeats, which contain a core repeating unit four nucleotides in length, are most often employed in forensic investigations. The number of tandem repeats varies per individual, and therefore STRs have a high degree of discrimination. Because it is a PCR-based technique and targets small DNA markers ranging in size from approximately 100 to 400 base pairs, there is a greater likelihood of producing a genetic profile from degraded DNA samples when the PCR target is small due to the fact that the longer stretches of the genome are broken apart during the degradation process.

The forensic community in the USA currently relies upon a standardized set of at least 20 STR loci for forensic genetic analyses, which are available in commercial multiplex kits. The standardization of this process allows a direct comparison of genetic profile results between various US laboratories and law enforcement agencies (Anđelinović et al. 2005; Butler 2007; Foran 2006a; Schneider 2007). There are, however, currently no international standards for genetic investigations. The development of universal standards could benefit both individual investigations and the identification of mass disaster victims.

Mitochondrial DNA

Mitochondrial DNA is located outside the cell nucleus within cytoplasmic organelles called mitochondria. Each mitochondrion may contain multiple identical copies of the mitochondrial genome (an average 2.6 mtDNA molecules per mammalian cell), and cells may contain multiple mitochondria (variation in values between cell types and also temporally within a single cell based on energy requirements), creating a situation where the mtDNA exists in hundreds to thousands of copies within each cell (Robin and Wong 1988). Therefore, there is a higher probability of obtaining analyzable mtDNA than nucDNA from degraded biological samples. Due to its unique inheritance pattern in comparison to the autosomal chromosomes, mtDNA is extensively employed in population-level analyses investigating anthropological questions such as population movement and population relationships. The mitochondrial genome displays uniparental inheritance, follows the maternal lineage, and does not participate in the process of genetic recombination (shuffling) as seen in the autosomal chromosomes. In other words, an individual's mtDNA will be the same as all of his or her consanguineous maternal relatives. In addition, the entire sequence (16,569 base pairs) of the mitochondrial genome is well-understood and has been extensively studied for population variability. Population-level studies have revealed that due to its high mutation rate, the mtDNA sequence is often geographically specific (Anderson et al. 1981; Cavalli-Sforza 1998; Giles et al. 1980; Kaestle and Horsburgh 2002; Mulligan 2006; von Haeseler et al. 1995).

Mitochondrial DNA sequence analysis is also important in forensic investigations when nuclear analysis is not possible or to supplement profiles generated from regions of the nuclear genome (Alaeddini et al. 2010; Butler and Levin 1998; Coble et al. 2009; Leney 2006). Similar to forensic nucDNA analyses, investigations of the mtDNA for forensic applications also focus on noncoding regions, because areas of the genome that do not code for proteins are more polymorphic among individuals. While forensic nucDNA analysis involves a comparison of different-sized STR amplicons (length polymorphisms), mtDNA analysis is more time-consuming, as it involves a direct sequence comparison of portions of the mitochondrial genome (sequence polymorphisms). Specifically, a segment of the mitochondrial genome is PCR-amplified, sequenced, and compared to the corresponding sequence of a missing person or a (usually) close maternal relative. Since the mitochondrial genome is shared by all relatives within a consanguineous maternal lineage, it can only provide a circumstantial identification. In other words, it is not individualizing to the point that it can provide a positive identification, as it cannot distinguish between the mitochondrial genome of mothers and their offspring or maternal aunts and maternal grandmothers (Alaeddini et al. 2010; Butler and Levin 1998; Harvey and King 2002). In addition, other members of the population at large may share a common mtDNA sequence due to very ancient common ancestry. For example, around 50% of individuals of

Western European descent share a common mtDNA sequence called haplogroup H. This same sequence is found in frequencies of 25%–30% in the Near East and up to 61% in some North African populations (Ottoni et al. 2010; Richards et al. 2002).

Y-Chromosome DNA

The Y-chromosome is part of the nuclear genome, yet its uniparental inheritance pattern enables it to be employed in population analyses in ways similar to mtDNA. The Y-chromosome is the smallest human chromosome, and 95% of its structure consists of a nonrecombining sequence block referred to as the NRY (*nonrecombining portion of the Y-chromosome*) (Jobling and Tyler-Smith 2003). Since the NRY is passed relatively unchanged through the paternal lineage, it can be used to address questions regarding population variability and population movement (Hammer et al. 2001; Scheinfeldt et al. 2006; Underhill et al. 2000).

While not as frequently utilized as traditional nucDNA STR analyses in forensic situations, the Y-chromosome could be useful in male-specific identifications. Y-chromosome-specific STRs are the most frequently used markers for identification purposes involving Y-chromosome DNA (Jobling et al. 1997; von Wurmb-Schwark et al. 2003). The same NRY sequence, however, is shared by all relatives within a consanguineous paternal lineage and can only provide a circumstantial identification.

Molecular Diagenesis

Molecular diagenesis refers to changes that accumulate in a molecule, like DNA, as the result of degradation, modification, and interaction with the exogenous environment. It is intimately linked to the chemical processes involved in cell death and postmortem decomposition. Cell death may proceed via *apoptosis, necrobiosis*, or *autolysis* depending on various intrinsic and extrinsic signals (Chapter 3). Apoptosis is an enzymatically dependent programmed cell death that removes damaged or diseased cells from the body. Necrobiosis is natural cell death that provides a mechanism for the replacement of cells that are no longer functioning properly. Apoptosis and necrobiosis do not play a major factor in human decomposition, because these processes refer to cell death in the living body. Autolysis is cell death due to the rupture of the cellular membranes and a release of enzymes liberated from membrane-bound cellular organelles called lysosomes. This process occurs in response to the lack of oxygen needed to generate cellular energy (ATP), as the cell is no longer in contact with circulating blood. ATP is essential in the operation of membrane pumps, which maintain concentration gradients within the cell, and the synthesis of intercellular molecules. In the absence of oxygen, the cell will switch to anaerobic respiration to produce ATP, which ultimately lowers the pH of the cell. These cellular changes result in the rupture of cellular membranes and the release of enzymes that will degrade the cellular structures, including the DNA (Alaeddini et al. 2010; Gill-King 1997).

The DNA contained within a cell begins to degrade immediately following cell death, as it is no longer protected by the repair mechanisms that counteract in vivo DNA damage. DNA degradation results from strand breakage, chemical modifications, and microbial attack. These degradative processes reduce the yield of high-molecular-mass DNA molecules and increase the chance of subsequent PCR failure (Alaeddini et al. 2010; Allentoft et al. 2012; Bär et al. 1988; Binladen et al. 2006; Eglinton et al. 1991; Handt et al. 1994; Höss et al. 1996; Richter et al. 1988; Rogan and Salvo 1990). Much of what is known about DNA degradation has been investigated in vitro, and it is assumed that the chemical processes occur the same way in cells that are not being studied in controlled laboratory settings (Lindahl 1993; Lindahl and Andersson 1972; Lindahl and Nyberg 1972, 1974). A thorough understanding of molecular diagenesis, however, remains daunting due to the high number of variables influencing postmortem DNA degradation in tissues.

A major complicating factor in retrieving analyzable DNA from older tissues is the reduced size of template molecules. Strand breakage reduces the DNA molecules to, on average, under 200 base pairs in length in older soft tissues and skeletal remains (Foran 2006a; Höss et al. 1996; Pajnič 2016). A large portion of strand breakage is caused by autolytic processes that occur soon after cell death as the molecules are digested by the enzymes liberated from lysosomes. As the nuclear membrane degrades, the nucDNA located within becomes vulnerable to attack from these enzymes. The DNA is digested by *nucleases*, a category of enzymes capable of cleaving the phosphodiester bonds holding adjoining nucleotides together along the DNA molecule. *Endonucleases* act to cleave the DNA molecules into smaller pieces, while *exonucleases* detach nucleotides from the terminal ends of the DNA molecule and gradually reduce it into smaller pieces (Bär et al. 1988; Child 1995; Lynnerup 2007; Rogan and Salvo 1990; Thomas and Pääbo 1993). This process usually begins with the degradation of easily accessible DNA into high molecular weight fragments. As the histone proteins that participate in DNA folding are digested by other liberated enzymes called proteases, the DNA is vulnerable to random fragmentation by endonucleases (Alaeddini et al. 2010).

In addition to endogenous enzymes, microbes contribute significantly to decomposition (Lynnerup 2007). Autolysis is followed by putrefaction, where anaerobic bacteria decompose the macromolecules of the body, such as lipids, carbohydrates, proteins, and nucleic acids. The ruptured cells release nutrient-rich fluids that further encourage microbial growth. The putrefaction phase is followed by a longer phase of aerobic and anaerobic microbial decomposition of organic material. The complex process of decomposition by microbes occurs as the decomposers release enzymes that degrade macromolecules like DNA into smaller pieces (Alaeddini et al. 2010; Bär et al. 1988; Rogan and Salvo 1990). For a more detailed discussion of microbial alteration of bone, refer to Chapter 2, this volume.

Chemical modifications that occur over long periods can be equally problematic for subsequent DNA analysis, and those molecules that survive the initial autolytic actions are subject to damage via *hydrolysis* and *oxidation*. Hydrolysis is the addition of water to a chemical bond, and results in the cleavage of the N-glycosyl bond holding the nitrogenous base to the deoxyribose sugar in the DNA nucleotide and breakage of the phosphodiester bonds in the DNA backbone. Oxidative damage results in modified bases that block the extension of the DNA polymerase during the PCR process or result in loss of ability to incorporate the appropriate complimentary base during PCR replication, as well as cleavage of the sugar and phosphate backbone (Eglinton et al. 1991; Höss et al. 1996; Lindahl 1993). Other chemical reactions that may complicate later analysis include DNA concatemerization, whereby DNA molecules form cross-links with proteins or other DNA molecules (Alaeddini et al. 2010).

In a living cell, each DNA nucleotide forms a chemical bond with eight to ten water molecules, making it highly reactive and the target for multiple chemical reactions (Alaeddini et al. 2010). This affinity of DNA for water molecules makes it vulnerable to hydrolysis. In the living cell, the DNA is maintained by continuous DNA repair. In dead tissues, the DNA will continue to attract water molecules, even in dry microenvironments, and is thus a target for hydrolytic damage. Hydrolytic damage results in *deamination* (loss of an amine group) of bases, as well as *depurination* (loss of adenine and guanine) and *depyrimidination* (loss of thymine and cytosine). Such modifications will halt or inhibit the PCR process. In addition, apurinic sites can further contribute to strand breakage by leading to the cleavage of the phosphodiester bonds along the backbone of the DNA molecule. Therefore, over long periods depurination will lead to short DNA fragments (Bada et al. 1999; Burger et al. 1999; Handt et al. 1994; Lindahl 1993).

The DNA located within a human cell is continually exposed to oxygen and therefore susceptible to oxidative stress. There are elaborate repair mechanisms, however, that function to protect the DNA from mutagenesis during the lifetime of the cell that are not present after the death of the cell. In addition to intracellular oxygen radicals produced by the mitochondria, oxygen radicals are ubiquitous in the environment and can extensively damage DNA molecules. Oxidative damage results in modified bases and the misincorporation of bases during replication events, such as during PCR amplification. Oxidation acts to remove the 3′ hydroxyl group that serves as a primer for the DNA polymerase enzyme that participates in chain elongation. In addition, oxidation can result in base lesions, whereby the nucleotides lose their ring structure and cause helical distortion that can interfere with subsequent genetic analyses (Lindahl 1993; Richter et al. 1988; Rogan and Salvo 1990).

Skeletal DNA

The preservation of the skeleton and skeletal DNA is variable from case to case, and significant variability is even witnessed among remains from a single archaeological site (Bell et al. 1996; Hagelberg et al. 1991; Haynes et al. 2002; Hedges 2002; Hedges and Millard 1995; Parsons and Weedn 1997; Ricaut et al. 2005). The extent of skeletal DNA degradation is, in part, related to gross bone degradation. Bone is a complex tissue consisting of inorganic calcium phosphate (mostly hydroxyapatite) and organic collagen protein components. As the bone degrades, the ratio of the inorganic to organic portions changes while the bone exchanges chemical constituents with the depositional environment. The rate of *bone diagenesis*, the complex process of degradation and modification to the chemical and/or structural properties of bone, is based on the leaching of the various inorganic and organic components of the osseous tissue, whose rate of loss is heavily dependent upon depositional environment and intrinsic bone factors. Studies suggest that as the inorganic portion of bone degrades, so does the skeletal DNA (Götherström et al. 2002; Vass 2001; Von Endt and Ortner 1984; White and Hannus 1983).

Analyzable DNA often persists within hard tissues for much longer periods than in soft tissues, as conditions within the bone may provide some protection against DNA degradation (Lassen et al. 1994). Bone has a low water and degradative enzyme content, which may shield against some of the hydrolytic damage and other chemical damage experienced by DNA contained within soft tissues. Bone also acts as a physical barrier that can protect the DNA from ultraviolet (UV) light, which is a major cause of the dimerization of bases and interstrand/intrastrand cross-links, and can prevent some larger enzymes or microbes from gaining access to the molecular material (Child 1995; Parsons and Weedn 1997; Rogan and Salvo 1990). Since UV light damages DNA molecules through thymine–thymine dimerization, it is often used as a sterilizing agent in laboratory settings (Aslanzadeh 2004).

Skeletal DNA becomes bound to the hydroxyapatite portion of bone as the negatively charged phosphate groups in the DNA molecules become attracted to the positively charged calcium ions of the hydroxyapatite (Götherström et al. 2002). This process stabilizes the DNA and provides some protection against the most common chemical and environmental factors acting to degrade the DNA molecules. For example, adsorption of the DNA molecules to the hydroxyapatite portion of bone results in a twofold reduction in depurination rates. Depurination is a major factor contributing to DNA degradation and reduced template size. The relationship between the skeletal DNA and hydroxyapatite may be one factor contributing to the preservation of DNA in skeletal tissues for long periods. In addition to the structural stability provided by adsorption of the DNA to the hydroxyapatite, this process might render the DNA physically inaccessible to larger enzymes that act to degrade the DNA molecules (Geigl 2002; Hedges and Millard 1995; Lindahl 1993).

Molecular Taphonomy

Molecular taphonomy is the study of those factors that influence molecular diagenesis and explores the impact of the various intrinsic and extrinsic forces influencing molecular integrity. Different molecules will degrade at different rates and are dependent upon the particular local environment, making a full understanding of the molecular diagenesis of DNA over long periods difficult due to the complexity and number of variables involved. While several variables have been identified as instrumental in the preservation or degradation of biological molecules, these variables do not work in isolation but rather within a complex web of interactions (discussed subsequently). In addition, as mentioned previously, DNA degradation is influenced by the rate and level of bone degradation, since the skeletal DNA binds to the hydroxyapatite. As the inorganic component of the bone degrades, the DNA is released from the hydroxyapatite and is no longer stabilized or protected.

Postmortem Interval (PMI)

Multiple studies have demonstrated that depositional environment is a more important factor in DNA preservation than the absolute age of the DNA sample (Dobberstein et al. 2008; Hagelberg and Clegg 1991; Haynes et al. 2002; Hochmeister et al. 1991; Latham 2003; Leney 2006; Meyer et al. 2000). A study by Perry et al. (1988) attempted to use the degradation rate of DNA isolated from human ribs obtained at autopsy to estimate the PMI. They incubated the bones at either high or low humidity at room temperature and took samples for DNA analysis at selected time intervals. They found variation in the amount of degradation for samples that were collected at the same time interval, suggesting that DNA does not follow a specific degradation trajectory that can be used to predict time since death. They did find, however, that humidity had a more profound impact on DNA degradation, as the samples incubated at low humidity were much less degraded than those incubated at high humidity. Kaiser et al. (2008) sampled 11 femora with PMIs ranging from one to over 200 years to investigate relationships between time since death and DNA degradation. While they found no correlation between PMI and DNA quantity, they did find that DNA degradation into smaller fragments is a time-dependent process.

Hagelberg et al. (1991) investigated the relationship between gross bone preservation, histological preservation, and DNA recovery in human bone and found that their thirteenth-century bone samples consistently produced better PCR amplification results than their seventeenth-century bone samples. They analyzed skeletal DNA isolated from human femora and found gross, microscopic, and molecular preservation to be better in the older skeletal remains. The authors suggested that this may be due to soil geochemistry or burial depth, supporting the observation that DNA preservation is not directly related to the time since death of the individual.

Allentoft et al. (2012) investigated the rate of DNA decay in a large fossil assemblage recovered from similar geographic environments. Utilizing a large sample size of 158 nonhuman bones with radiocarbon ages already determined, they found only 38.6% of the variation in DNA preservation in their samples could be explained by radiocarbon age. While they did provide some data for predicting DNA degradation over time, the conclusions support previous studies that emphasize the importance of environmental factors in influencing DNA degradation rates.

Depositional Environment

Temperature

Temperature influences both gross bone and DNA preservation. This relationship is due to the fact that degradation at both the macroscopic and microscopic levels is the result of a complicated series of chemical reactions, and all chemical reactions are greatly influenced by temperature. Initial decomposition processes like autolysis and putrefaction display a maximum chemical activity at 34°C–40°C, and there is a two- to threefold decrease in the reaction rate for simple chemical processes for each 10°C decrease in temperature (Bär et al. 1988; Lindahl 1993). For example, depurination is a major contributor to DNA degradation, and the activation energy for this chemical reaction is highly temperature-dependent (Allentoft et al. 2012; Götherström et al. 2002). Thus, the chemistry of biological degradation is slowed at lower temperatures.

Temperature is one of the most important factors governing microbial growth and therefore one of the most important factors governing the rate and extent of microbial attack on biological material. In general, microbial activity associated with decomposition is greater at warmer temperatures. Microorganisms have a profound impact on gross bone diagenesis by leading to collagen loss and increased bone porosity. The microbes that participate in the decomposition of bone produce enzymes called collagenases that allow them to digest mineralized collagen. Since the hydroxyapatite crystals of bone are surrounded by collagen, the loss of collagen weakens the mineral component of bone and makes it more vulnerable to degradation. Some decomposers have the ability to participate in a specialized form of degradation called *microscopic focal destructions* (MFD). MFDs are small tunnels in the bone mediated by microbial dissolution of the mineral component of bone (Child 1995; Collins et al. 2002; Hedges 2002; Chapter 2). On the molecular scale, invading decomposers release enzymes that degrade molecules like DNA into smaller pieces and therefore reduce overall DNA quantity and quality. Thus, decomposer activity as well as chemical degradation are slowed at cooler temperatures. This relationship is supported by studies that have found that DNA retrieved from bones deposited in cooler environments are better preserved than DNA retrieved from bones deposited in warmer environments (Burger et al. 1999; Höss et al. 1996; Smith et al. 2003).

There are also circumstances, however, where mild heating has been found to be beneficial in obtaining high quantities of skeletal DNA. For example, mild heating may accelerate the loss of in situ water from bone and reduce hydrolytic damage (Geigl 2002). In addition, bones subjected to warm temperatures are more friable and may more easily release the DNA bound to their mineral phase. Reidy et al. (2009) compared ease of DNA isolation from an 800-year-old skeleton recovered from a subterranean cave in southern Mongolia and a recently deceased individual from the United States. She encountered difficulty in extracting skeletal DNA from the modern individual and relative ease in isolating DNA from the 800-year-old skeleton. This inspired her to bake a bone sample from the modern individual to mimic the mummification process and environmental conditions of the Mongolian cave. After the bone baking process (100.0°C for 72 h), she was able to isolate analyzable DNA from the modern sample and suggested that bones exposed to heat and extreme drying more readily release the DNA bound to the hydroxyapatite, making the probability of subsequent genetic analysis more likely. Madonna et al. (2015) built upon this observation by systematically baking bones at 90°C for varying periods of time up to 72 h. They found an increase in DNA yield and no difference in DNA quality in comparison to the unbaked controls. Edson (2019c) analyzed nearly 4000 samples from individuals buried in tropical environments and determined that chemical modification introduced by environmental contamination was more important in determining the success of genetic testing then environmental temperatures.

Geochemistry

The geochemistry of the depositional environment is an important extrinsic factor impacting biological diagenesis. The presence of groundwater in soil has a profound influence on bone diagenesis that can also affect DNA preservation. It participates in many of the chemical reactions that occur during decomposition, such as diffusion and hydrolysis (Eglinton et al. 1991). Groundwater enters and percolates through bone, depending upon the available free energy required to move the water from the soil into the bone matrix. The free energy is determined mostly by the size of the pores in the bone; therefore, the pore structure for any given bone will dictate how it interacts with groundwater. As bone dissolution progresses, the pores become larger and act as channels for hydraulic flow, leading to a greater loss of bone mineral (Hedges 2002; Hedges and Millard 1995; Roberts et al. 2002). The greater the dissolution of the inorganic component of the bone, the greater the chance of DNA loss as the DNA molecules dissociate from the protection of the hydroxyapatite.

At the microscopic level, moisture content impacts initial autolytic processes that can damage DNA (Carter et al. 2010). Initial rapid desiccation of tissues tends to limit early hydrolytic damage of the DNA, while aqueous environments favor hydrolytic reactions that fragment DNA molecules and cause the loss of purine bases from the nucleotides (Eglinton et al. 1991; Poinar and Stankiewicz 1999). The profound impact of moisture is likely a factor as to why soft tissues, with a high water content, are more readily decomposed and have poorer DNA preservation than osseous tissues. In addition, microbial activity is reduced at the extreme ends of moisture content (in more aqueous and extremely dry environments), and microbes have a profound effect on degradation, as previously discussed (Lynnerup 2007).

The chemical composition of the depositional environment influences the rate and extent of mineral leaching from the bone and the uptake of different solutes from the soil. In the majority of cases, the osseous tissue is not in complete chemical equilibrium with the depositional environment and will begin to degrade as mineral is leached from the bone (Collins et al. 2002). In addition, bone crystallinity (the degree of order within the crystal lattice) increases over time as exogenous materials from the depositional environment are incorporated into the mineral component of bone. Living bone displays irregularities in the hydroxyapatite matrix, and after death a net increase in hydroxyapatite crystallinity is observed over time. The exact mechanisms are poorly understood, yet it appears that this process (called *recrystallization*) may involve the dissolution and re-precipitation of the smallest hydroxyapatite crystals (Hedges 2002; Hedges and Millard 1995; Pate and Hutton 1988; Roberts et al. 2002; Surovell and Stiner 2001; Tuross et al. 1989). Since skeletal DNA is tightly bound to the hydroxyapatite, chemical changes regarding the hydroxyapatite have an influence on DNA preservation in the bone, with a negative correlation being found between hydroxyapatite crystallinity and DNA preservation. This occurs because the process of dissolution and re-precipitation releases the DNA from the hydroxyapatite, leaving it vulnerable to further degradation (Götherström et al. 2002). The interaction of soil minerals and bone is a complex process, and a more in-depth discussion can be found by referring to Chapters 5 and 12.

In addition, solutes may be incorporated into the bone that are later co-purified with the extracted skeletal DNA and serve as PCR inhibitors that limit subsequent genetic analyses (Amory et al. 2012; Davoren et al. 2007; Edson 2019c; Kemp et al. 2006; Lee et al. 2009; Tuross 1994). Such PCR inhibitors act to block the enzymatic reactions during the PCR process. The hydroxyapatite crystal lattice gains an affinity for acidic molecules as the collagen component is lost from the bone. An example is the humic acid group of molecules, which are produced as a by-product during microbial digestion of organic material. Humic acid is a known PCR inhibitor and is ubiquitous in soil. The uptake of humic acids by osseous materials is recognized by a brown staining on bones that have been in contact with soils or decaying organic materials (Burger et al. 1999; Hedges 2002; Chapter 5). The presence and abundance of particular elements in bone also may provide clues as to the original depositional environment. For example, the uptake of iron and manganese indicates an oxidizing environment, which promotes DNA degradation (Elliott and Grime 1993).

Soil chemistry also heavily influences microbial activity. The appropriate nutrients and ions must be available to the decomposers living in the soil and the substances that are toxic to them must be absent. The two major processes involved in microbial decomposition of bone are the production of inorganic ions from the oxidation of organic compounds (mineralization) and the incorporation of inorganic molecules into the microbial protoplasm (immobilization). These processes are highly dependent upon the cycling of nitrogen and calcium in that particular position of the ecosystem. Furthermore, different depositional environments will be home to different decomposer communities that will produce different decay processes. This may refer to different geographical locations or different burial depths within a single geographic location, as the top several feet of soil will have a different microbial community than that found at deeper depths (Child 1995; Eglinton et al. 1991).

Bone dissolution and DNA degradation are highly influenced by soil and groundwater pH (Hedges and Millard 1995). Since most of the living human body is near neutral pH, tissues and DNA are better preserved in neutral or slightly alkaline environments (Burger et al. 1999). Soil that has a neutral pH tends to have calcium and phosphate concentrations similar to those found in bone and leads to a slower rate of bone degradation. Soil that has a low pH tends to have lower calcium and phosphate concentrations in comparison to bone and will lead to a faster rate of bone degradation as H+ ions from the soil replace the calcium ions of the bone (Foran 2006a; Hedges 2002; White and Hannus 1983). The pH of the immediate bone environment also can be altered by microorganism activity. Microbes will produce acids as they decompose collagen. The H+ ions from these acids also can then replace the calcium in the hydroxyapatite of the bone and contribute to the chemical breakdown of the bone (White and Hannus 1983).

The rate of recrystallization of hydroxyapatite is also influenced by pH. This rearrangement of the mineral component of the bone leads to problems with gross structural integrity such as cracking and the dissolution of osteons (Piepenbrink 1989). Such alterations of bone mineral content can increase bone dissolution and impact the DNA located within the bone by accelerating DNA degradation. The greatest damage to skeletal DNA, however, occurs at pH extremes, as bone provides some buffering effect against pH-induced damage from surrounding acidic or alkaline soils (Smith et al. 2003).

While a neutral or slightly alkaline pH tends to produce better-preserved bones, it also provides an optimal environment for microbial activity. The majority of known microorganisms grow optimally at or around neutral pH, as cell chemistry is especially sensitive to pH changes. The internal cellular proteins of the microbes are destroyed if the cytoplasm becomes too acidic or too alkaline (Collins et al. 2002). Thus, environmental pH influences both chemical and microbial digestion of biological material.

Processing Techniques

Different processing techniques for soft tissue removal employed by forensic anthropologists may also influence DNA quantity and quality. Several studies (see below) have tested the relationship between various maceration techniques and the success of subsequent genetic analyses. There is general agreement that some soft tissue removal procedures are more detrimental to subsequent DNA analysis than others.

Arismendi et al. (2004) assessed the influence of five maceration procedures on subsequent nuclear STR and amelogenin amplification success. Rennick et al. (2005) analyzed the effects of three processing techniques on subsequent mtDNA amplification success. Steadman et al. (2006) analyzed the relationship between 10 heat and chemical maceration techniques and PCR amplification success using both nucDNA and mtDNA primers. Lee et al. (2010) tested the impact of nine different processing techniques on subsequent nuclear STR analysis in human bone samples. Frank et al. (2015) analyzed the influence of hot water maceration and visualization techniques that emit radiation, CT and X-ray, on subsequent nuclear STR amplification. All of these studies found techniques that use heat for short periods to be the most effective in terms of cleaning the bones and yielding successful genetic analyses and that boiling for long periods or the use of large volumes of chemicals like bleach were detrimental to DNA integrity and analysis. Long-term exposure to heat can denature and degrade the DNA molecules, and cleaning chemicals like household bleach (NaClO) are oxidizing agents that can promote DNA damage. Exposing the DNA molecules to bleach will cause oxidative damage such as base modifications and chlorinated base products and will inhibit the PCR process. In fact, high concentrations of bleach are often employed to destroy contaminating surface DNA from biological samples (like bone) and laboratory equipment (Kemp and Smith 2005).

Embalming may also influence subsequent genetic analysis. Chemical mortuary treatments can enhance DNA degradation or modify the DNA molecules and thus complicate

PCR analysis. Embalming fluids like formaldehyde (CH_2O) act to concatemerize the DNA molecules and inhibit PCR amplification by preventing denaturation of the double-stranded DNA. Sterilizing agents like lime (CaO) increase the rate of alkaline hydrolysis and accelerate DNA damage. While mortuary practices may not be a significant factor in the majority of forensic cases, it is a potential complicating factor when bodies need to be exhumed for genetic testing (Koon et al. 2008).

Skeletal Element

At the macroscopic level, small bones are generally not as well-preserved as large bones in the archaeological record (Grupe 1988; Von Endt and Ortner 1984; Chapters 4 and 17). Since DNA preservation is influenced by gross bone preservation, this suggests that smaller bones may not be as reliable as large bones in producing DNA profiles. There are studies, however, that indicate that analyzable DNA can be isolated from even poorly preserved bones and suggest that in situations where a large number of bones are available for analysis, it is better to choose samples from bones with better gross preservation (Haynes et al. 2002; Richards et al. 1995). On the other hand, several studies found that more weathered bones produced higher quantities of analyzable DNA due to bone friability (Foran 2006b; Misner et al. 2009). This observation is similar to those studies that found bones subjected to warm temperatures produce better quantity DNA (as discussed previously). The studies by Foran (2006b) and Misner et al. (2009) analyzed human skeletal remains from an historic cemetery located in Pennsylvania, USA and a Late Bronze Age/Early Iron Age burial mound located in eastern Albania. Each bone in the study was given an overall weathering score ranging from 0 to 5 based on gross bone preservation (Behrensmeyer 1978). These scores were then compared to the amount of extracted skeletal DNA and mtDNA amplification success. The bones with the higher weathering scores (stages 4 and 5) produced greater quantities of analyzable DNA and had higher PCR amplification success rates.

In addition, several studies have indicated that bone type influences the quantity of recoverable DNA isolated from skeletal remains. In general, compact bone tends to yield a greater quantity of extracted DNA than spongy bone. Compact bone contains approximately 20,000 osteocytes per cubic mm and can yield up to 3–10 ng/mg of DNA. Differential yield between compact and spongy bone may be due to: (1) the higher moisture content of spongy bone leading to increased hydrolytic damage; (2) the increased rigidity of the cortical bone due to tightly packed hydroxyapatite crystals and the greater binding affinity of DNA molecules; (3) the more porous nature of spongy bone leading to an increased rate of leaching of the mineral matrix and greater exposure of the DNA molecules to destructive enzymes; or (4) that cortical bone tends to protect trapped osteocytes and other cells better than spongy bone and therefore provides better protection of the cellular DNA (Foran 2006b; Leney 2006; Pajnič 2016; Parsons and Weedn 1997; White and Hannus 1983). Miloš et al. (2007) found the highest success rates for subsequent genetic analyses on samples taken from long bone shafts and virgin teeth, with lower PCR success displayed by samples from the vertebrae, ilium, and cranium. Their study was based on a large sample of over 25,000 human skeletal elements from the former Yugoslavia that were subjected to nuclear STR analysis. In addition, they found differences in PCR success rates between the compact long bones of the legs (femur at 86.9%, tibia at 75.9%, and fibula at 62.5%) and arms (humerus at 46.2%, radius at 24.5%, and ulna at 22.8%), which is a pattern found by other investigations with smaller sample sizes investigating various sampling loci including mtDNA (Edson 2019a, b; Edson et al. 2004; Foran 2006b; Leney 2006; Mundorff et al. 2009). Although Edson (2019a) concluded that the efficiency of different extraction techniques and choice of testing platform are just as important as bone type in influencing different success rates of genetic testing, she recommended considering the circumstances of the particular case and ultimate goals in terms of genetic testing when choosing a skeletal element for genetic analyses.

Antinick and Foran (2019) utilized nonhuman bone to demonstrate that in addition to variation in DNA quantity based on bone type, there is also considerable variation in DNA quantity obtained from different areas of the same bone. DNA quantity values were acquired using quantitative real-time PCR. They concluded that long bone epiphyses generally had more quantifiable DNA than long bone diaphyses in fresh bones and that no regional differences in DNA quantity values were detected in bones allowed to decompose for six months on the ground surface.

Virgin teeth have been found to be excellent reservoirs for DNA (Dobberstein et al. 2008; Edson 2019b; Kaestle and Horsburgh 2002; Pajnič 2016; Ricaut et al. 2005). Enamel, dentin, and cementum are the three main tissues found in human teeth. Enamel covers the crown surface and contains an organic and inorganic fluorapatite component similar to bone. While both bone and teeth are mineralized tissues, their morphology and biochemistry are different and lead to different decay processes. Bone is more porous than enamel and degrades more rapidly, as pore number and size influence the interaction of the particular biological element (bone or tooth) with available groundwater and access of enzymes to the DNA. In addition, enamel is more mineralized than bone. Enamel consists of 95% inorganic fluorapatite, while only 65% of adult bone consists of inorganic matrix, suggesting even greater protection to the DNA bound to the inorganic portion of the tooth (Dobberstein et al. 2008; Lambert et al. 1985; Marieb and Hoehn 2010; Schwartz et al. 1991; Woelfel and Scheid 1997).

Area of the Genome

In addition to the different inheritance patterns of nucDNA versus mtDNA, the two regions of the genome also have different biological properties. The two types of human DNA have different cellular locations, with the nucDNA found within the cell nucleus and the mtDNA contained within extranuclear organelles. There are two copies of nucDNA per cell, one maternal and one paternal copy. In other words, an individual inherits one of each chromosome 1–23 from their mother and one of each chromosome 1–23 from their father. On the other hand, the mtDNA is present in multiple identical copies per cell, because each mitochondrion contains multiple copies of the mitochondrial genome, and most human cells contain multiple mitochondria. The higher copy number of the mtDNA per cell results in a greater probability that analyzable segments of the mtDNA will be recovered versus the nucDNA genome (Foran 2006a; Kaestle and Horsburgh 2002). Schwarz et al. (2009) determined the ratio of nucDNA to mtDNA in six mammoth bone samples using quantitative PCR. While the numbers were variable, all six bones displayed a preferential preservation of mitochondrial over nucDNA, with ratios ranging from 245:1 to 17,369:1, suggesting that targeting the mitochondrial genome for genetic analysis of old skeletal remains may prove more fruitful than targeting the nuclear genome. While the mtDNA may be easier to obtain from degraded samples, it does not contain as much individualizing information as the nuclear genome.

The small size of the mitochondrial genome in terms of bp and the circular structure of the mtDNA might make it less susceptible to enzymatic modification than nucDNA (Alaeddini et al. 2010; Foran 2006a; Hagelberg et al. 1991). In addition, the mtDNA is enclosed within the double membrane of the mitochondrion. The compartmentalization of the mitochondrion due to an inner and outer membrane is essential in creating cellular energy via the electron transport chain. This compartmentalization may provide more protection to the mtDNA. There are other explanations for the preferential preservation of the mtDNA over the nucDNA, including a negative influence of the chromatin folding structure of the nucDNA (Collins et al. 2002; Foran 2006a; Schwarz et al. 2009).

It is important to understand that nucDNA is more vulnerable to degradation, as this may influence the choice of genetic analytical techniques and the interpretation of genetic data from skeletal remains. The nucDNA may be degraded beyond the point at which it is detectable using PCR-based analyses, making mtDNA sequence analysis the only option. Many forensic DNA laboratories, however, will try to amplify a nucDNA profile first, as it is more individualizing. In addition, degraded nucDNA may produce incomplete STR profiles due to stochastic fluctuations like allelic dropout. In cases of positive identification, the ability to compare a complete genetic profile from the unknown remains to a known sample originating from the missing individual or a close family member increases the statistical strength in the identification. Therefore, an analyst may choose to sequence a portion of the mitochondrial genome or reduce the size of the nuclear STR amplicon by moving the primers closer to the STR repeat region (Butler et al. 2003; Opel et al. 2006).

The techniques utilized to extract and analyze DNA in forensic settings continue to advance quickly, allowing for smaller amounts of degraded DNA to be analyzed more efficiently and more rapidly. Extraction buffers that provide complete demineralization and increasingly sensitive DNA testing modalities allow for the generation of DNA profiles from samples that may have failed to do so just a few years ago. In addition, as laboratories begin to adopt next-generation sequencing (NGS) technology, the ability to conduct more complex genome analyses will allow for the inclusion of additional genetic markers. For example, single nucleotide polymorphisms (SNPs) that can serve to individualize further the genetic profile and provide phenotypic information about the individual that contributed the biological sample (Brandhagen et al. 2020; Butler 2015; Jäger et al. 2017; Tao et al. 2019; Wang et al. 2015; 2018; Yang et al. 2014).

Concluding Remarks

The analysis of DNA extracted from skeletal remains requires destructive sampling of the skeleton. Therefore, it is important that the analyst understand those environments that are most favorable for DNA preservation, those areas of the skeleton that are most successful in producing PCR amplifiable DNA for subsequent genetic analysis, and the appropriate genetic tests to employ to address their particular research or forensic questions. General scientific literacy regarding DNA survivability in skeletal remains can reduce the amount of human skeletal material destroyed for subsequent genetic testing in potentially futile situations.

Recommendations

Depositional Environment

A variety of environmental factors act collectively to influence the rate and extent of DNA damage. Therefore, knowledge of the depositional environment is important in predicting the probability of successful genetic testing. Genetic analysis has been successful from skeletal remains recovered in both indoor and outdoor contexts, including for the latter both burials and surface scatters. Individual variation, however, in the production of a successful DNA profile can be related partly to differences in the depositional environments of individual cases and even to variations between microenvironments within the same skeleton. Furthermore, processing techniques produce an artificial environment that can influence the ability to generate a usable DNA profile.

Temperature

The chemical reactions that contribute to DNA degradation occur at a faster rate in higher temperatures. Thus, cooler depositional environments will favor DNA preservation, but recent studies suggest that mild heating may lead to increased DNA yields, as it makes the bones more brittle and better able to release the bound skeletal DNA.

Moisture Levels

Hydrolytic reactions are a major contributor to DNA damage. These chemical reactions require water molecules and result in the loss of DNA bases and strand breakage. Such modifications can complicate later PCR-based genetic analyses. DNA has an affinity for water molecules, and therefore the more groundwater or humidity that is present in the depositional environment, the greater the probability of DNA damage.

Oxygen Levels

Oxidative reactions result in modified DNA bases, as electrons are lost to oxygen molecules. The DNA base modifications or lesions interfere with the ability of the DNA polymerase to copy the target DNA template during the PCR process. Therefore, oxygen-rich environments will contribute to greater DNA damage and potential complications with later genetic analysis.

Exposure to Microorganisms

Both endogenous and exogenous microorganisms contribute to the decomposition of biological material. Microbes digest mineralized collagen, which makes the mineral portion of bone and the DNA bound to it more prone to damage. In addition, decomposing microorganisms release enzymes that fragment DNA molecules. The more access microbes have to the decomposing body, the greater the probability of DNA degradation.

Chemical Composition of the Soil

The chemical composition of the soil of the depositional environment has an impact on bone crystallinity. There is a correlation between crystallinity and the ability to PCR-amplify successfully extracted skeletal DNA, with the higher the crystallinity, the lower the PCR amplification success rate. In addition, the soil might contain solutes that copurify with the DNA and inhibit the PCR amplification process. Thus, knowledge of the chemical composition of the soil of the depositional environment can be informative in understanding failed PCR amplification attempts.

pH

The human body is near neutral pH. Thus, DNA is less prone to damage in environments consisting of soil and groundwater at near neutral pH. Environments of extreme pH (very acidic or very alkaline) encourage the disruption of cellular membranes and the denaturation of the DNA molecules.

Bone Type

DNA degrades more rapidly in soft tissue than in skeletal elements. Therefore, skeletal material should be given preference over decomposed or mummified soft tissues for subsequent PCR-based genetic analyses. The sampling of skeletal remains for genetic analysis should not be based on convenience but on an understanding of those skeletal elements likely to yield successful genetic analyses. Multiple lines of independent research have demonstrated that the cortical portions of the bones of the lower limb or the teeth are the most successful in generating a DNA profile. The teeth, femora shafts, and tibiae shafts consistently produce high success rates. In addition, the metatarsals and pedal phalanges have shown to be very reliable in recent investigations. Success rates for the cranium (in particular, the petrous portion of the temporal bone) and other areas of the skeleton vary widely from study to study and among laboratory facilities.

Sampling Strategy

Forensic anthropologists employ a variety of processing techniques to remove soft tissues from skeletal elements. The removal of a bone for genetic testing before or after processing is often the decision of the individual laboratory. The effects of different processing techniques on subsequent DNA quality and quantity have been thoroughly investigated, and some processing procedures have been demonstrated to be more detrimental to subsequent genetic testing than others. In general, those methods that employ heat for shorter periods of time and without caustic chemicals tend to be the most effective in cleaning the bones while producing subsequently successful DNA analyses.

The decision to provide a tooth, bone, or portion of a bone to a DNA laboratory for genetic analyses varies widely among forensic facilities. This is a decision that should be made in close consultation between the forensic anthropologist and the DNA analyst. Some DNA laboratories prefer to isolate DNA from teeth and others from bone. If choosing a bone for analysis, the decision must be made whether to cut a portion to be sent for genetic testing or send an entire bone. The process of isolating DNA from skeletal tissue is a destructive process. DNA extraction techniques vary across laboratories and, based upon the procedure employed, typically require a minimum of 0.2–5.0 g of skeletal material. Laboratories often require more bone than employed in a single extraction due to the removal of outer layers that may contain contaminating DNA or the possibility of additional extractions if the first attempt fails. If sending a whole bone, all observations, measurements, and photographs must be completed prior to genetic testing, with the assumption that some or all of the bone will be consumed during the DNA extraction process. If cutting a bone, strict cross-contamination precautions must be employed to prevent questioning of the DNA results by opposing counsel. In addition, cutting should be done in areas that do not destroy important landmarks used in osteological analyses (Figure 15.1).

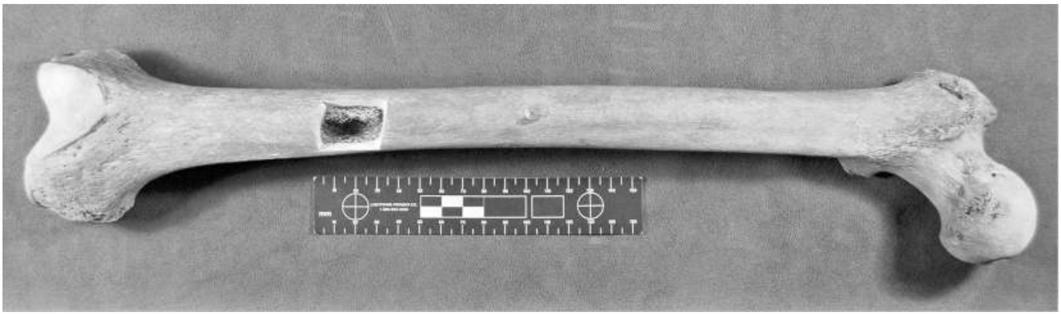

Figure 15.1 Right femur sampled for subsequent genetic analysis. The scale is in cm.

Appropriate Genetic Tests

Choosing the appropriate genetic test to perform on the unidentified individual is dependent upon the question that needs to be addressed, the ability to obtain a reference sample, and the condition of the DNA-yielding tissue. The majority of forensic situations necessitate positive identification of the unknown skeletal remains, and thus nucDNA analysis. Nuclear DNA, however, is more prone to degradation, and such analyses may not be feasible. In such situations, mtDNA analysis may contribute to a collection of circumstantial information strong enough to identify the individual.

In other situations, mtDNA is the most appropriate target for analysis. Questions regarding familial relationships within a cemetery population, population movement across geographic space, or population relationships extensively utilize mtDNA analysis due to its unique inheritance pattern and geographic specificity. In addition, ancient DNA studies extensively rely on mtDNA analysis, because it is less susceptible to degradation than nucDNA.

Thermal Alterations to Bone

Thermally altered bone is frequently encountered in a forensic setting, and fire may be the major contributor to the destruction of recognizable soft tissue features that would have allowed identification of the individual without forensic anthropological analysis. In some more extreme situations, osseous identifiers may no longer exist, necessitating the need for another means of identification, namely the generation of a DNA profile. The successful generation of a DNA profile from burned bone varies across studies and is dependent upon the degree of thermal destruction, as well as the extraction and amplification procedures used by the DNA laboratory. Several studies have reported the ability to generate genetic information from bones ranging from charred to cremated at temperatures up to 600°C (Federchook et al. 2019; Imaizumi et al. 2014; Schwark et al. 2011; Ubelaker 2009; Zgonjanin et al. 2015).

In reality, the skeletonized cases encountered by a forensic scientist will be less than pristine in terms of available elements and condition. The bones and teeth will be scattered, fragmented, buried, burned, damaged by carnivores and other living organisms in the environment, sun-bleached, and handled by crime scene technicians, to name just a few possibilities. In many situations, the need for a positive identification is so great that any available biological element will be processed in hopes of obtaining a DNA profile. The recommendations in this chapter are just that: general recommendations aimed at saving time, money, and the unwarranted destruction of skeletal material.

Different DNA laboratories use different DNA extraction techniques, which greatly influence subsequent DNA yield regardless of the area of the skeleton sampled for DNA testing. Different DNA laboratories are optimized for different loci and use slightly different PCR parameters, again influencing DNA typing success regardless of skeletal element. In addition, technological advances regarding low-quality and low-quantity DNA are increasing rapidly in their ability to extract and successfully generate DNA profiles. Many DNA laboratories lag behind cutting-edge technology, as optimization and the creation of new standard operating procedures are timely and costly. Thus, a basic working knowledge of DNA survivability in skeletal remains is essential when working in fields that aim at identifying unknown individuals.

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References

Alaeddini, R., S. J. Walsh, and A. Abbas (2010) Forensic implications of genetic analyses from degraded DNA—A review. *Forensic Science International: Genetics* 4:148–157.

Allentoft, M. E., M. Collins, D. Harker, J. Haile, C. L. Oskam, M. L. Hale, P. F. Campos, J. A. Samaniego, M. T. P. Gilbert, E. Willerslev, G. Zhang, R. P. Scofield, R. N. Holdaway, and M. Bunce (2012) The half-life of DNA in bone: Measuring decay kinetics in 158 dated fossils. *Proceedings of the Royal Society B* 279:4724–4733.

Alonso, A., P. Martín, C. Albarrán, P. García, O. García, L. F. de Simón, J. García-Hirschfeld, M. Sancho, C. de la Rúa, and J. Fernández-Piqueras (2004) Real-time PCR designs to estimate nuclear and mitochondrial DNA copy number in forensic and ancient DNA studies. *Forensic Science International* 139(2–3):141–149.

Amory, S., R. Huel, A. Bilic, O. Loreille, and T. J. Parsons (2012) Automatable full demineralization DNA extraction procedure from degraded skeletal remains. *Forensic Science International* 6(3):398–406.

Anđelinović, S., D. Sutlović, I. E. Ivkosić, V. Skaro, A. Ivkosić, F. Paić, B. Rezić, M. Definis-Gojanović, and D. Primorac (2005) Twelve-year experience of skeletal remains from mass graves. *Croatian Medical Journal* 46(4):530–539.

Anderson, S., A. T. Bankier, B. G. Barrell, M. H. L. de Bruijn, A. R. Coulson, J. Drouin, I. C. Eperon, D. P. Nierlich, B. A. Roe, F. Sanger, P. H. Schreier, A. J. H. Smith, R. Staden, and I. G. Young (1981) Sequence and organization of the human mitochondrial genome. *Nature* 290:457–465.

Antinick, T. C., and D. R. Foran (2019) Intra- and inter-element variability in mitochondrial and nuclear DNA from fresh and environmentally exposed skeletal remains. *Journal of Forensic Sciences* 64(1):88–97.

Arismendi, J. L., L. E. Baker, and K. J. Matteson (2004) Effects of processing techniques on the forensic DNA analysis of human skeletal remains. *Journal of Forensic Sciences* 49(5):930–934.

Aslanzadeh, J. (2004) Preventing PCR amplification carryover contamination in a clinical laboratory. *Annals of Clinical and Laboratory Science* 34(4):389–396.

Bada, J. L., X. S. Wang, and H. Hamilton (1999) Preservation of key biomolecules in the fossil record: Current knowledge and future challenges. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 354(1379):77–87.

Bär, W., A. Kratzer, M. Machler, and W. Schmid (1988) Postmortem stability of DNA. *Forensic Science International* 39(1):59–70.

Bell, L. S., M. F. Skinner, and S. J. Jones (1996) The speed of post mortem change to the human skeleton and its taphonomic significance. *Forensic Science International* 82(2):129–140.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Paleobiology* 4(2):150–162.

Binladen, J., C. Wiuf, M. T. Gilbert, M. Bunce, R. Barnett, G. Larson, A. D. Greenwood, J. Haile, S. Y. Ho, A. J. Hansen, and E. Willerslev (2006) Assessing the fidelity of ancient DNA sequences amplified from nuclear genes. *Genetics* 172(2):733–741.

Brandhagen, M. D., R. S. Just, and J. A. Irwin (2020) Validation of NGS for mitochondrial DNA casework at the FBI Laboratory. *Forensic Science International: Genetics* 44:102151.

Burger, J., S. Hummel, B. Herrmann, and W. Henke (1999) DNA preservation: A microsatellite-DNA study on ancient skeletal remains. *Electrophoresis* 20(8):1722–1728.

Butler, J. M. (2007) Short tandem repeat typing technologies used in human identity testing. *Biotechniques* 43(4):2–5.

Butler, J. M. (2015) The future of forensic DNA analysis. *Philosophical Transactions of the Royal Society B* 370(1674):20140252.

Butler, J. M., and C. L. Levin (1998) Forensic applications of mitochondrial DNA. *Trends in Biotechnology* 16(4):158–162.

Butler, J. M., Y. Shen, and B. R. McCord (2003) The development of reduced size STR amplicons as tools for analysis of degraded DNA. *Journal of Forensic Sciences* 48(5):1054–1064.

Cale, C. M., M. E. Earll, K. E. Latham, and G. L. Bush (2016) Could secondary DNA transfer falsely place someone at the scene of a crime? *Journal of Forensic Sciences* 61(1):196–203.

Carter, D. O., D. Yellowlees, and M. Tibbett (2010) Moisture can be the dominant environmental parameter governing cadaver decomposition in soil. *Forensic Science International* 200(1–3):60–66.

Cavalli-Sforza, L. L. (1998) The DNA revolution in population genetics. *Trends in Genetics* 14(2):60–65.

Child, A. M. (1995) Towards an understanding of the microbial decomposition of archaeological bone in the burial environment. *Journal of Archaeological Science* 22(2):165–174.

Coble, M. D., O. M. Loreille, M. J. Wadhams, S. M. Edson, K. Maynard, C. E. Meyer, H. Niederstatter, C. Berger, B. Berger, A. B. Falsetti, P. Gill, W. Parson, L. N. Finelli (2009) Mystery solved: The identification of the two missing Romanov children using DNA analysis. *PLoS ONE* 4(3):1–9.

Collins, M. J., C. M. Nielsen-Marsh, J. Hiller, C. I. Smith, J. P. Roberts, R. V. Prigodich, T. J. Wess, J. Csapo, A. R. Millard, and G. Turner-Walker (2002) The survival of organic matter in bone: A review. *Archaeometry* 44(3):383–394.

Davoren, J., D. Vanek, R. Konjhodzic, J. Crews, E. Huffine, and T. J. Parsons (2007) Highly effective DNA extraction method for nuclear short tandem repeat testing of skeletal remains from mass graves. *Croatian Medical Journal* 48(4):478–485.

Dobberstein, R. C., J. Huppertz, N. von Wurmb-Schwark, and S. Ritz-Timme (2008) Degradation of biomolecules in artificially and naturally aged teeth: Implications for age estimation based on aspartic acid racemization and DNA analysis. *Forensic Science International* 179(2–3):181–191.

Edson, S. M. (2019a) Extraction of DNA from skeletonized postcranial remains: A discussion of protocols and testing modalities. *Journal of Forensic Sciences* 64(5):1312–1323.

Edson, S. M. (2019b) Getting ahead: Extraction of DNA from skeletonized cranial material and teeth. *Journal of Forensic Sciences* 64(6):1646–1657.

Edson, S. M. (2019c) The effect of chemical compromise on the recovery of DNA from skeletonized human remains: A study of three World War II era incidents recovered from tropical locations. *Forensic Science Medicine and Pathology* 15(6):1–13.

Edson, S. M., J. P. Ross, M. D. Coble, T. J. Parsons, and S. M. Barritt (2004) Naming the dead—Confronting the realities of rapid identification of degraded skeletal remains. *Forensic Science Review* 16(1):63–90.

Eglinton, G., G. A. Logan, R. P. Ambler, J. J. Boon, and W. R. K. Perizonius (1991) Molecular preservation [and Discussion]. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 333(1268):315–328.

Elliott, T. A., and G. W. Grime (1993) Examining the diagenetic alteration of human bone material from a range of archaeological burial sites using nuclear microscopy. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 77(1–4):537–547.

Elwick, K., C. Mayes, and S. Hughes-Stamm (2018) Comparative sensitivity and inhibitor tolerance of GlobalFiler® PCR Amplification and Investigator® 24plex QS kits for challenging samples. *Legal Medicine* 32:31–36.

Ensenberger, M. G., K. A. Lenz, L. K. Matthies, G M. Hadinoto, J. E. Schienman, A. J. Przech, M. W. Morganti, D. T. Renstrom, V. M. Baker, K. M. Gawrys, M. Hoogendoorn, C. R. Steffen, P. Martín, A. Alonso, H. R. Olson, C. J. Sprecher, and D. R. Storts (2016) Developmental validation of the PowerPlex1 Fusion 6C System. *Forensic Science International: Genetics* 21: 134–144.

Federchook, T. J., J. T. Pokines, K. Crowley, and C. M. Grgicak (2019) Recovery of DNA from teeth exposed to variable temperatures. *Forensic Anthropology* 2(3):143–151

Foran, D. R. (2006a) *Final Report Increasing the Predictability and Success Rate of Skeletal Evidence Typing: Using Physical Characteristics of Bone as a Metric for DNA Quality and Quantity.* NIJ Grant # 2002-IJ-CX-K016. Michigan State University, East Lansing, MI.

Foran, D. R. (2006b) Relative degradation of nuclear and mitochondrial DNA: An experimental approach. *Journal of Forensic Sciences* 51(4):766–770.

Frank, E. M., A. Z. Mundorff, and J. M. Davoren (2015) The effect of common imaging and hot water maceration on DNA recovery from skeletal remains. *Forensic Science International* 257:189–195.

Geigl, E. M. (2002) On the circumstances surrounding the preservation and analysis of very old DNA. *Archaeometry* 44(3):337–342.

Giles, R. E., H. Blanc, H. M. Cann, and D. C. Wallace (1980) Maternal inheritance of human mitochondrial DNA. *Proceedings from the National Academy of Science* 77(11):6715–6719.

Gill, P., J. Whitaker, C. Flaxman, N. Brown, and J. Buckelton (2000) An investigation of the rigor of interpretation rules for STRs derived from less than 100 pg of DNA. *Forensic Science International* 112(1):17–40.

Gill-King, H. (1997) Chemical and ultrastructural aspects of decomposition. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 109–126. CRC Press, Boca Raton, FL.

Götherström, A., M. J. Collins, A. Angerbjörn, and K. Lidén (2002) Bone preservation and DNA amplification. *Archaeometry* 44(3):395–404.

Grupe, G. (1988) Impact of the choice of bone samples on trace element data in excavated human skeletons. *Journal of Archaeological Science* 15(2):123–129.

Hammer, M. F., T. M. Karafet, A. J. Redd, H. Jarjanazi, S. Santachiara-Benercetti, H. Soodyall, and S. L. Zegura (2001) Hierarchical patterns of global Y-chromosome diversity. *Molecular Biology and Evolution* 18(7):1189–1203.

Hagelberg, E., L. S. Bell, T. Allen, A. Boyde, S. J. Jones, and J. B. Clegg (1991) Analysis of ancient bone DNA: Techniques and applications. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences* 333(1268):399–407.

Hagelberg, E., and J. B. Clegg (1991) Isolation and characterization of DNA from archaeological bone. *Proceedings of the Royal Society of London. Series B: Biological Sciences* 244(1309):45–50.

Handt, O., M. Höss, M. Krings, and S. Pääbo (1994) Ancient DNA: Methodological challenges. *Cellular and Molecular Life Sciences* 50(6):524–529.

Harvey, M., and M. King (2002) The use of DNA in the identification of postmortem remains. In *Advances in Forensic Taphonomy: Method, Theory, and Archeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 473–486. CRC Press, Boca Raton, FL.

Haynes, S., J. B. Searle, A. Britman, and K. M. Dobney (2002) Bone preservation and ancient DNA: The application of screening methods for predicting DNA survival. *Journal of Archaeological Science* 29(6):585–592.

Hedges, R. E. (2002) Bone diagenesis: An overview of processes. *Archaeometry* 44:319–328.

Hedges, R. E., and A. R. Millard (1995) Bones and groundwater: Towards the modeling of diagenetic processes. *Journal of Archaeological Science* 22(2):155–164.

Hochmeister, M. N., B. Budowle, U. V. Borer, U. Eggmann, C. T. Comey, and R. Dirnhofer (1991) Typing of deoxyribonucleic acid (DNA) extracted from compact bone from human remains. *Journal of Forensic Sciences* 36(6):1649–1661.

Höss, M., P. Jaruga, T. H. Zastawny, M. Dizdaroglu, and S. Pääbo (1996) DNA damage and DNA sequence retrieval from ancient tissues. *Nucleic Acids Research* 24(7):1304–1307.

Imaizumi, K., K. Taniguchi, and Y. Ogawa (2014) DNA survival and physical and histological properties of heat-induced alterations in burnt bones. *International Journal of Legal Medicine* 128(3):439–446.

Jäger, A. C., M. L. Alvarez, C. P. Davis, E. Guzmán, Y. Han, L. Way, P. Walichiewicz, D. Silva, N. Nguyen Pham, G. Caves, J. Bruand, F. Schlesinger, S. J. K. Pond, J. Varlaro, K. M. Stephens, and C. L. Holt (2017) Developmental validation of the MiSeq FGx forensic genomics system for targeted next generation sequencing in forensic DNA casework and database laboratories. *Forensic Science International: Genetics* 28:52–70.

Jobling, M. A., A. Pandya, and C. Tyler-Smith (1997) The Y chromosome in forensic analysis and paternity testing. *International Journal of Legal Medicine* 110(3):118–124.

Jobling, M. A., and C. Tyler-Smith (2003) The human Y chromosome: An evolutionary marker comes of age. *Nature Reviews Genetics* 4:598–612.

Kaestle, F. A., and K. A. Horsburgh (2002) Ancient DNA in anthropology: Methods, applications and ethics. *Yearbook of Physical Anthropology* 35:92–130.

Kaiser, C., B. Bachmeier, C. Conrad, A. Nerlich, H. Bratzke, W. Eisenmenger, and O. Peschel (2008) Molecular study of time dependent changes in DNA stability in soil buried skeletal residues. *Forensic Science International* 177(1):32–36.

Kalmár, T., C. Z. Bachrati, A. Marcsik, and I. Raskó (2000) A simple and efficient method for PCR amplifiable DNA extraction from ancient bones. *Nucleic Acids Research* 28(12):1–4.

Kemp, B. M., C. Monroe, and D. G. Smith (2006) Repeat silica extraction: A simple technique for the removal of PCR inhibitors from DNA extracts. *Journal of Archaeological Science* 33(12):1680–1689.

Kemp, B. M., and D. G. Smith (2005) Use of bleach to eliminate contaminating DNA from the surface of bones and teeth. *Forensic Science International* 154(1):53–61.

Koon, H. E. C., O. M. Loreille, A. D. Covington, A. F. Christensen, T. J. Parsons, and M. J. Collins (2008) Diagnosing post-mortem treatments which inhibit DNA amplification from US MIAs buried at the Punchbowl. *Forensic Science International* 178(2–3):171–177.

Lambert, J. B., S. Vlasak, C. B. Szpunar, and J. E. Buikstra (1985) Bone diagenesis and dietary analysis. *Journal of Human Evolution* 14(5):477–482.

Lassen, C., S. Hummel, and B. Herrmann (1994) Comparison of DNA extraction and amplification from ancient human bone and mummified soft tissue. *International Journal of Legal Medicine* 107:152–155.

Latham, K. E. (2003) *The Relationship Between Bone Condition and DNA Preservation.* M.S. Thesis, University of Indianapolis, Indianapolis, IN.

Lee, E. J., J. G. Luedtke, J. L. Allison, C. E. Arber, D. A. Merriwether, and D. W. Steadman (2010) The effects of different maceration techniques on nuclear DNA amplification using human bone. *Journal of Forensic Sciences* 55(4):1032–1038.

Lee, H. Y., M. J. Park, N. Y. Kim, J. E. Sim, W. I. Yang, and K. J. Shin (2009) Simple and highly effective DNA extraction methods from old skeletal remains using silica columns. *Forensic Science International: Genetics* 4(5):275–280.

Leney, M. D. (2006) Sampling skeletal remains for ancient DNA (aDNA): A measure of success. *Historical Archaeology* 40(3):31–49.

Lindahl, T. (1993) Instability and decay of the primary structure of DNA. *Nature* 362:709–715.

Lindahl, T., and A. Andersson (1972) Rate of chain breakage at apurinic sites in double-stranded deoxyribonucleic acid. *Biochemistry* 11(19):3618–3623.

Lindahl, T., and B. Nyberg (1972) Rate of depurination of native deoxyribonucleic acid. *Biochemistry* 11(19):3610–3618.

Lindahl, T., and B. Nyberg (1974) Heat-induced deamination of cytosine residues in deoxyribonucleic acid. *Biochemistry* 13:3405–3411.

Lynnerup, N. (2007) Mummies. *Yearbook of Physical Anthropology* 50:162–190.

Madonna, M. E., K. E. Latham, and S. P. Nawrocki (2015) The utility of baking bone to increase skeletal DNA yield. *Journal of Forensic Identification* 65(2):107–117.

Marieb, E. N., and K. Hoehn (2010) *Human Anatomy and Physiology*. Benjamin Cummings, San Francisco, CA.

Meyer, E., M. Wiese, H. Bruchhaus, M. Claussen, and A. Klein (2000) Extraction and amplification of authentic DNA from ancient human remains. *Forensic Science International* 113(1–3):87–90.

Miloš, A., A. Selmanović, L. Smajlović, R. L. Huel, C. Katzmarzyk, A. Rizvić, and T. J. Parsons (2007) Success rates of nuclear short tandem repeat typing from different skeletal elements. *Croatian Medical Journal* 48(4):486–493.

Misner, L. M., A. C. Halvorson, J. L. Dreier, D. H. Ubelaker, and D. R. Foran (2009) The correlation between skeletal weathering and DNA quality and quantity. *Journal of Forensic Sciences* 54(4):822–828.

Mulligan, C. J. (2006) Anthropological applications of ancient DNA: Problems and prospects. *American Antiquity* 71(2):365–380.

Mundorff, A. Z., E. J. Bartelink, and E. Mar-Cash (2009) DNA preservation in skeletal elements from the World Trade Center disaster: Recommendations for mass fatality management. *Journal of Forensic Sciences* 54(4):739–745.

Oostdik, K., K. Lenz, J. Nye, K. Schelling, D. Yet, S. Bruski, J. Strong, C. Buchanan, J. Sutton, J. Linner, N. Frazier, H. Young, L. Matthies, A. Sage, J. Hahn, R. Wells, N. Williams, M. Price, J. Koehler, M. Staples, K. L. Swango, C. Hill, K. Oyerly, W. Duke, L. Katzilierakis, M. G. Ensenberger, J. M. Bourdeau, C. J. Sprecher, B. Krenke, and D. R. Storts (2014) Developmental validation of the PowerPlex1 Fusion System for analysis of casework and reference samples: A 24-locus multiplex for new database standards. *Forensic Science International: Genetics* 12:69–76.

Opel, K. L., D. T. Chung, J. Drábek, N. E. Tatarek, M. L. Jantz, and B. R. McCord (2006) The application of miniplex primer sets in the analysis of degraded DNA from human skeletal remains. *Journal of Forensic Sciences* 51(2):351–356.

Ottoni, C., G. Primativo, B. Hooshiar Kashani, A. Achilli, C. Martínez-Labarga, G. Biondi, A. Torroni, and O. Rickards (2010) Mitochondrial haplogroup H1 in North Africa: An early Holocene arrival from Iberia. *PLoS ONE* 5(10):e13378.

Pajnič, I. Z. (2016) Extraction of DNA from human skeletal material. *Methods in Molecular Biology* 1420:89–108.

Parsons, T. J., and V. W. Weedn (1997) Preservation and recovery of DNA in postmortem specimens and trace samples. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 109–126. CRC Press, Boca Raton, FL.

Pate, F. D., and J. T. Hutton (1988) The use of soil chemistry data to address post-mortem diagenesis in bone mineral. *Journal of Archaeological Science* 15(6):729–739.

Perry, W. L., W. M. Bass, W. S. Riggsby, and K. Sirotkin (1988) The autodegradation of deoxyribonucleic acid (DNA) in human rib bone and its relationship to the time interval since death. *Journal of Forensic Sciences* 33(1):144–153.

Piepenbrink, H. (1989) Examples of chemical changes during fossilization. *Applied Geochemistry* 4(3):273–280.

Poinar, H. N., and B. A. Stankiewicz (1999) Protein preservation and DNA retrieval from ancient tissues. *Proceedings of the National Academy of Sciences of the United States of America* 96(15):8426–8431.

Reidy, K. M., A. Gareis, D. Sun, R. AuClair, T. Wong, R. Lang, H. Meng, H. M. Coyle, H. C. Lee, and A. B. Harper (2009) Gender identification differences observed for DNA quantification versus STR genotyping of mummified human remains—How it relates to human identifications in forensic science. *Investigative Sciences Journal* 1(1):1–10.

Rennick, S. L., T. W. Fenton, and D. R. Foran (2005) The effects of skeletal preparation techniques on DNA from human and non-human bone. *Journal of Forensic Sciences* 50(5):1016–1019.

Ricaut, F. X., C. Keyser-Tracqui, E. Crubézy, and B. Ludes (2005) STR-genotyping from human medieval tooth and bone samples. *Forensic Science International* 151(1):31–35.

Richards, M., V. Macaulay, A. Torroni, and H. Bendelt (2002) In search of geographical patterns in European mitochondrial DNA. *American Journal of Human Genetics* 71(5):1168–1174.

Richards, M. B., B. C. Sykes, and R. E. M. Hedges (1995) Authenticating DNA extracted from ancient skeletal remains. *Journal of Archaeological Science* 22(2):291–299.

Richter, C., J. W. Park, and B. N. Ames (1988) Normal oxidative damage to mitochondrial and nuclear DNA is extensive. *Proceedings of the National Academy of Sciences of the United States of America* 85(17):6465–6467.

Roberts, S. J., C. I. Smith, A. Millard, and M. J. Collins (2002) The taphonomy of cooked bone: Characterizing boiling and its physico-chemical effects. *Archaeometry* 44(3):485–494.

Robin, E. D., and R. Wong (1988) Mitochondrial DNA molecules and virtual number of mitochondria per cell in mammalian cells. *Journal of Cellular Physiology* 136(3):507–513.

Rogan, P. K., and J. J. Salvo (1990) Study of nucleic acids isolated from ancient remains. *American Journal of Physical Anthropology* 33:195–214.

Scheinfeldt, L., F. Friedlaender, J. Friedlaender, K. Latham, G. Koki, T. Karafet, M. Hammer, and J. Lorenz (2006) Unexpected NRY chromosome variation in Northern Island Melanesia. *Molecular Biology and Evolution* 23(8):1628–1641.

Schneider, P. M. (2007) Scientific standards for studies in forensic genetics. *Forensic Science International* 165(2–3):238–243.

Schwark, T., A. Heinrich, A. Preuße-Prange, and N. von Wurmb-Schwark (2011) Reliable genetic identification of burnt human remains. *Forensic Science International: Genetics* 5(5):393–399.

Schwartz, T. R., E. A. Schwartz, L. Mierszerski, L. McNally, and L. Kobilinsky (1991) Characterization of deoxyribonucleic acid (DNA) obtained from teeth subjected to various environmental conditions. *Journal of Forensic Sciences* 36(4):979–990.

Schwarz, C., R. Debruyne, M. Kuch, E. McNally, H. Schwarcz, A. D. Aubrey, J. Bada, and H. Poinar (2009) New insights from old bones: DNA preservation and degradation in permafrost preserved mammoth remains. *Nucleic Acids Research* 37(10):1–15.

Smith, C. I., A. T. Chamberlain, M. S. Riley, C. Stringer, and M. J. Collins (2003) The thermal history of human fossils and the likelihood of successful DNA amplification. *Journal of Human Evolution* 45(3):203–217.

Steadman, D. W., L. L. DiAntonio, J. J. Wilson, K. E. Sheridan, and S. P. Tammariello (2006) The effects of chemical and heat maceration techniques on the recovery of nuclear and mitochondrial DNA from bone. *Journal of Forensic Sciences* 51(1):11–17.

Surovell, T. A., and M. C. Stiner (2001) Standardizing infra-red measures of bone mineral crystallinity: An experimental approach. *Journal of Archeological Science* 28(6):633–642.

Tao, R., W. Qi, C. Chen, J. Zhang, Z. Yang, W. Song, S. Zhang, and C. Li C (2019) Pilot study for forensic evaluations of the Precision ID GlobalFiler™ NGS STR Panel v2 with the Ion S5™ system. *Forensic Science International: Genetics* 43:102147.

Thomas, K., and S. Pääbo (1993) DNA sequences from old tissue remains. *Methods in Enzymology* 224:406–419.

Tuross, N. (1994) The biochemistry of ancient DNA in bone. *Experientia* 50(6):530–535.

Tuross, N., A. K. Behrensmeyer, E. D. Eanes, L. W. Fisher, and P. E. Hare (1989) Molecular preservation and crystallographic alterations in a weathering sequence of wildebeest bones. *Applied Geochemistry* 4(3):261–270.

Ubelaker, D. H. (2009) The forensic evaluation of burned skeletal remains: A synthesis. *Forensic Science International* 183(1–3):1–5.

Underhill, P. A., P. Shen, A. A. Lin, L. Jin, G. Passarino, W. Yang, E. Kauffman et al. (2000) Y chromosome sequence variation and the history of human populations. *Nature Genetics* 26:358–361.

Vass, A. A. (2001) Beyond the grave—Understanding human decomposition. *Microbiology Today* 28:190–192.

Von Endt, D. W., and D. J. Ortner (1984) Experimental effects of bone size and temperature on bone diagenesis. *Journal of Archaeological Science* 11(3):247–253.

von Haeseler, A., A. Sajantila, and S. Pääbo (1995) The genetical archaeology of the human genome. *Nature Genetics* 14(2):135–140.

von Wurmb-Schwark, N., S. Petermann, and R. Wegener (2003) Y-STR typing in forensic analysis. *International Congress Series* 1239:487–490.

Wang, H., J. Zhu, N. Zhou, Y. Jiang, L. Wang, W. He, D. Peng, Q. Su, J. Mao, D. Chen, W. Liang, and L. Zhang (2015) NGS technology makes microhaplotype a potential forensic marker. *Forensic Science International: Genetics Supplement Series* 5:e233–e234.

Wang, L., M. Chen, B. Wu, Y.-C. Liu, G.-F. Zhang, L. Jiang, X.-L. Xu, X.-C. Zhao, A.-Q. Ji, and J. Ye (2018) Massively parallel sequencing of forensic STRs using the Ion Chef™ and the Ion S5™ XL systems. *Journal of Forensic Sciences* 63(6):1692–1703.

White, E. M., and L. A. Hannus (1983) Chemical weathering of bone in archaeological soils. *American Antiquity* 48(2):316–322.

Woelfel, J. B., and R. C. Scheid (1997) *Dental Anatomy: Its Relevance to Dentistry*. Williams & Williams, Baltimore, MD.

Yang, Y., B. Xie, and J. Yan (2014) Application of next-generation sequencing technology in forensic science. *Genomics Proteomics Bioinformatics* 12(5):190–197.

Zgonjanin, D., S. Petković, M. Maletin, R. Vuković, and D. Drašković (2015) Case report: DNA identification of burned skeletal remains. *Forensic Science International: Genetics Supplement Series* 5:e444–e446.

Avian Taphonomy

16

JAMES T. POKINES
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Contents

> They say that Creon has sworn
> No one shall bury him, no one mourn for him,
> But this body must lie in the fields, a sweet treasure
> For carrion birds to find as they search for food.
>
> **—Sophocles**
> *Antigone,* translation by Dudley Fitts and Robert Fitzgerald

Introduction

The effect of birds upon osseous remains is one of the earliest taphonomic topics speculated on prior to the formalization of this field, in terms of how various types of birds might concentrate the bones of their small prey in favored feeding locations (Buckland 1823). This early interest and subsequent research into this topic may have been driven by its visibility and ubiquity: many raptor (predatory) bird species roost in the same location continuously for a large portion of a year, often raising a brood at that time. Their energy requirements are such that many trips per day with fresh prey to feed their young and themselves are necessary. The remains of these meals can build up substantial osseous assemblages in and under roosting sites, and many such roosts are reoccupied over multiple years, sometimes by different species in succession. Feeding often proceeds in a dramatic fashion, with

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whole prey gobbled up or torn into pieces for nestlings. These rather striking ecological proceedings (often occurring in urban/commensal settings as large raptors are reintroduced into these environments) may have spurred interest in the hunting and feeding habits of these charismatic species as determined from the remains of their feeding. Adding to this potential interest by humans into raptor activities may be the regurgitation of pellets, the undigested concentrated balls of fur, feathers, connective tissue, teeth, and bone, which also accumulate in and under raptor roosts in large quantities (Bunn et al. 1982). These are egested by many bird species (Glue 1970), not just owls (Order Strigiformes). Pellets often protect their contained osseous remains exceedingly well until their incorporation into sediments (Lyman et al. 2003). Raptors, therefore, are likely the fastest concentrators of osseous remains (as measured by element counts) in the animal world, outpacing such taxa as hyaenids and canids. As such, their behavior relevant to small vertebrate taphonomy has been widely researched (Andrews 1990; Baker 2012; Bocheński and Tornberg 2003; Pokines 1998; Pokines et al. 2011; Pokines and Kerbis Peterhans 1998).

Osseous accumulations by birds were recognized early as a boon to paleoecological reconstruction (Davis 1959; Southern 1954), as well as studies of extant ecosystems (Glading et al. 1943; Lovari et al. 1976; Moon 1940; Reed 1957). Many species of generalist avian predators are highly adept at sampling the small vertebrate community within their hunting radius, thus providing a relatively unpixelated snapshot of these species living in that area at that time. These remains also tend to be very undamaged and identifiable, depending upon the species of raptor (Andrews 1990; Mayhew 1977). Later research examined the taphonomic effects left behind on osseous remains relative to the accumulating agent, to identify and potentially control for the biases caused in species and body part representation (Cummings et al. 1976; Dodson and Wexlar 1979; Duke et al. 1975; Korth 1979; Levinson 1982; Mayhew 1977). This research has expanded to many species of raptors worldwide and the potentially unique taphonomic characteristics that they may leave on bone (Bocheński et al. 2009; Lloveras et al. 2014; Marín Arroyo and Margalida 2012; Reed 2005; Robert and Vigne 2002; Sanchis Serra et al. 2014; Sanders et al. 2003; Stewart et al. 1999; Terry 2010).

The taphonomic effects of large scavenging bird species upon large mammals are less well known, likely due to their lesser ability to transport large bones and concentrate them in easily analyzable samples. Remains are thus largely left at the initial death scene and not reconcentrated in a different location, potentially to become part of the fossil record. Remains left behind in surface scatters, therefore, are of lesser interest to paleoecological studies, but they are of course central to forensic anthropological sites where human remains have been deposited outdoors. The continued analysis of avian interaction with human remains is necessary to understand the physical alteration and movement of bone. Determination of these patterns may allow the separation of this source of taphonomic alteration from others of more direct forensic interest, including perimortem trauma, dismemberment, and loss of elements. The scavenging of soft tissue by birds or terrestrial scavengers also has the potential to alter the conclusions that may be drawn about postmortem interval (PMI) from patterns of decomposition and eventual skeletonization, since analysis of these relies in part upon observations of the degree of soft tissue loss (Megyesi et al. 2005). Scavenging birds also are capable of accessing some vertebrate remains that terrestrial scavengers cannot, including human remains suspended in the air due to hanging (Komar and Beattie 1998) or in some indoor settings (Dettling et al. 2001).

Raptor Predation upon Primates

Diurnal and nocturnal raptors are known to prey upon multiple extant species of nonhuman primates. Hart (2000) and Hart and Sussman (2008) noted that 81 species of raptors are known or suspected primate predators, out of a total of 176 predatory species of all kinds (including mammals, reptiles, etc.) known or suspected to exploit this food source. Some species, including the large, powerful African crowned eagle (*Stephanoaetus coronatus*), are primate specialists over at least part of their range and hunt in forest canopies for multiple species of large monkey (McGraw et al. 2006; Sanders et al. 2003). Predation is more prevalent where the raptors have the size advantage, but some species are known to kill and transport primates heavier than themselves (Hart 2000). Hart and Sussman (2008:138) tabulated that 46% of published eyewitness accounts of instances of primate predation involved raptors. This number may be inflated by the ability of raptors to arrive on a scene and swiftly depart despite the presence of humans witnessing their predatory activity, and the availability of primates within tree canopies where both they and their predators can be observed.

No known extant raptor species have been documented to prey upon adult humans, although the latter frequently are subject to attack in defense of self or nesting site (Parker 1999). Some instances of attacks by predatory birds upon children also are known, although a natural tendency to exaggeration of these events makes many claims suspect (Hart and Sussman 2008). Even large species such as golden eagles (*Aquila chrysaetos*) are limited in the size of their prey, which can include domestic calves (Phillips et al. 1996). Among North American taxa, golden eagles can, however, lift prey items heavier than their own body mass (Sørensen et al. 2008) and conceivably could transport juvenile human remains. Bald eagles (*Haliaeetus leucocephalus*) also fall into this range. In the Old World, multiple species have the ability to transport juvenile humans, including crowned eagles, Verreaux's eagles (*Aquila verreauxii*), martial eagles (*Polemaetus bellicosus*), and in South America, harpy eagles (*Harpia harpyja*) (Armstrong and Avery 2014; Gargett 1990; Gilbert et al. 2009; and pers. obs.). Larger species of extinct raptors had the potential to include humans more regularly as prey items (Scofield and Ashwell 2009). Only very large, flightless species (ostrich, *Struthio camelus*; and cassowary, *Casuarius* spp.) have been known to inflict fatal harm upon adult humans through direct physical attack (Kofron 1999). These rare instances do not result in feeding and further taphonomic alteration of human remains. Such interactions with human remains are primarily in the realm of scavenging bird species (see "Scavenging Birds" section, below).

Raptor predation is also relevant to extinct taxa of hominins and how their remains might have been incorporated into the fossil record. It has been posited that the type specimen for *Australopithecus africanus*, the Taung Child, was killed by a large eagle species and transported to its final deposition site (Berger 2006; Berger and Clarke 1995; Berger and McGraw 2007; De Ruiter et al. 2010; McGraw et al. 2006; Sanders et al. 2003). The estimated age at death is 3–4 years. The Taung site in South Africa is a large tufa accretion that encompasses over 24 fossil deposits of varying ages and accumulation mechanisms. The two limestone caverns that are most closely associated with the hypothesized provenience of the *A. africanus* skull are the Dart and Hrdlička Pinnacles, which also have yielded the remains of primarily smaller vertebrate fauna. These species are dominated by extinct baboon, rodents, hares, bats, birds, small antelopes, and hyraxes, all conforming in size to typical large eagle prey, with the majority of taxa having a body mass of less than 20 kg (Berger and Clarke 1995). These fauna also included multiple types of taphonomic damage typically caused by large birds of prey (Berger and Clarke 1995:280): depression fractures and puncture marks caused by talons; damage to the basicranium and crushing of the vault and facial bones to access cranial tissue; and V-shaped nicks in bone surfaces caused by beaks. Damage from eagle feeding also may take the form of gouges and scratches around the eye orbits (Berger and McGraw 2007). The scratch marks often appear in semi-parallel clusters and may result from gripping and manipulation of the skull by talons. Damage also may appear to the orbital floors (Berger 2006), which likely result from talons gripping around the more durable orbital margins (McGraw et al. 2006).

Scavenging Birds

Scavenging Birds and Human Remains

Many extant species of scavenging birds are known to feed upon human remains, among the many other large vertebrates that comprise their diet. Scavengers, by their very nature, have non-discriminating feeding habits, and the low levels of humans in their diets have more to do with human than scavenger behavior. Most human death preparation involves scavenger exclusion from remains as quickly as possible, but human remains deliberately left in outdoor situations or those from remote suicides or accidents are subject to scavenging birds. Some human body disposal practices deliberately expose human remains (often left on platforms, high rock outcrops, or in specially built towers with open roofs, thereby largely excluding terrestrial scavengers) to decompose and be consumed by scavenging birds. This process is termed *sky burial* and was practiced historically by groups on the Himalayan plateau, Zoroastrians in Persia and later in India, and possibly by some Native American tribes and groups in northern Asia, Thailand, and Korea (Martin 1996; van Dooren 2011). This practice by the Zoroastrians was well known in the ancient world and was documented by many writers in antiquity, including Herodotus (Trinkaus 1984). This practice also has been depicted in artwork at the Neolithic urban site of Çatal Hüyük in Anatolia (Turkey), dating to ca. 7000 BC (van Dooren 2011). Less formally, in the Roman Empire, bodies of the poor were sometimes disposed of on rubbish heaps (Nock 1932), presumably with subsequent feeding by vultures and other scavengers occurring. In modern and historical times in the Himalayas, the express purpose of this type of body disposal was dismemberment and leaving it exposed to be consumed, primarily by scavenging birds. Multiple edicts attempted to ban this practice, with apparently little effect until recent decades (Hamilton and Spradley 2011; Martin 1996). That human mortuary ritual treatment in multiple parts of the world relied upon the repeated actions of scavenging birds (and other taxa) in the disposal of their dead indicates the pervasive taphonomic influence that birds have had upon exposed human remains, whether these remains were exposed through deliberate action or other means. This strong association with death and the afterlife is likely why vultures appear in the artwork of so many cultures, including extensively in ancient Egypt (Houlihan and Goodman 1986), and the common presence of vulture remains in human sites in early Neolithic contexts in the Near East (Gourichon 2002).

Table 16.1 **New World (Family Cathartidae) Vulture Species**

Taxon	Common Name	Current Range (Houston 2001)
Cathartes aura	Turkey vulture	Southern Canada through all of South America
Cathartes burrovianus	Lesser yellow-headed vulture	Northern South America into Central America
Cathartes melambrotus	Greater yellow-headed vulture	Northern South America
Coragyps atratus	Black vulture	USA through most of South America
Gymnogyps californianus	California condor	California (USA) and surrounding area
Sarcoramphus papa	King vulture	Northern South America into Central America
Vultur gryphus	Andean condor	Andes mountain range, South America

Vultures

New World vultures and condors (Family Cathartidae) inhabit the tropical to temperate zones of North and South America (Table 16.1) and are most closely related to storks and herons (Ciconiiformes). Their fossil history dates back to the Eocene, 40–50 million years ago (Houston 2001). These species were more diverse during the Pleistocene (Stager 1964), and multiple extinctions may be traced to the loss of many species of mammalian megafauna from the New World at that time and the loss of this scavenging food resource. New World vultures have a distinct evolutionary history from Old World vultures (Subfamily Aegypiinae), which include the bearded vulture (*Gypaetus barbatus*) and griffon vulture (*Gyps fulvus*) and are related to common raptor species such as eagles and falcons (Houston 2001). The similarities in scavenging lifestyle among the two major vulture lineages worldwide therefore are due to evolutionary convergence. Most Old World vultures, like their New World vulture counterparts, are obligate scavengers for sustenance and do not hunt live prey for a significant portion of their diet (Ogada et al. 2012). Unlike some New World vultures, Old World vultures do not have a highly advanced olfactory sense and locate the carcasses upon which they feed primarily through sight. Some species of New World vultures (*Cathartes* spp.) locate the carcasses upon which they feed primarily through an acute sense of smell (Stager 1964), so some delay between death and the onset of carcass discovery and feeding is typical. Other adaptations to an obligate scavenging lifestyle (Houston 2001; van Dooren 2011) include large wing areas relative to body mass, designed for gliding long distances with lesser energy expenditure (i.e., soaring flight as opposed to powered flight) while in search of food; large home ranges; large fat reserves to allow storage of energy between feeding bouts; the ability to consume over 20% of their body mass at once; long, thin necks and long, hooked beaks evolved to reach into narrow spaces around bones for feeding; and a general lack of feathers on the head and upper neck also to facilitate feeding in narrow spaces.

Turkey Vultures (Cathartes aura)

Turkey vultures are easily distinguishable by their bright red head and dark plumage. Their adult body mass is around 850–2000 g, and their wingspan is around 180–200 cm (Houston 2001). This species is widespread, from southern Canada through South America (Demo et al. 2013), and its breeding range is expanding into southern Canada (Houston et al. 2011; Prior and Weatherhead 1991; Rabenold and Decker 1989). It tends to settle in communal roosting trees and foray out over a large home range in search of food. Coleman and Fraser

(1989) found that the turkey vultures they studied in western Pennsylvania, USA, spent from 33% to 27% of the day (varying seasonally) on the wing, primarily searching for food. Up to 15 km were covered in 1 day. The size of home ranges likely increases in environments where food resources are sparser. Thomaides et al. (1989) detected movement of up to 74 km from a home roost in west Texas based upon the availability of a distant food resource showing up in the diet. Coleman and Fraser (1989) measured average home ranges of turkey vultures in southern Pennsylvania and northern Maryland, USA, as 37,072 ha (143 miles^2). In addition to normal movement over their home ranges, turkey vultures are also seasonally migratory (Mandel et al. 2008; Rabenold and Decker 1989) between northerly and southerly portions of their ranges to ameliorate winter food scarcity and temperature extremes. Some individuals, however, over-winter in the northern portions of their range.

Movement within the home range is frequent. Roost locations often circulate among multiple reused sites with many single-use locations within the home range. Roosts may serve as centers for information exchange among individuals returning to it at night, regarding food sources located that day and still viable the next day (Prior and Weatherhead 1991; Rabenold 1987). Foraging usually is singular or in small groups of only a few individuals (Stewart 1978), but larger foraging groups numbering up to 21 individuals have been noted (summarized in Prior 1990). Feeding, however, often involves agonistic displays, with more dominant turkey vultures feeding before subordinate individuals (Prior and Weatherhead 1991). This subordination extends both ways in interspecies interactions: turkey vultures are subordinate to, for example, larger species of vultures and red-tailed hawks, but crows are subordinate to turkey vultures and usually are driven away from carcasses that the crows locate first (Prior and Weatherhead 1991; Wallace and Temple 1987). This successive use of the same carcass also may benefit the smaller species, in that the larger species are more able to open up larger carcasses so that they can be exploited more fully by (generally) smaller species feeding later (Wallace and Temple 1987).

Habitat use by turkey vultures often includes forested areas (Coleman and Fraser 1989). Reports of the exploitation of road kills are variable, with some researchers noting the importance of the resource (Yahner et al. 1990) and others noting its lack (Coleman and Fraser 1989), despite its presumed availability. Turkey vulture diet is based upon the availability of fresh, scavengeable carcasses within their home range, which naturally tends to reflect the abundances of species within that environment. Dietary analysis frequently is achieved by the identification of hairs and feathers within egested pellets collected under home roosts, as the bone fragments contained within are usually too small to identify from large food species (Hiraldo et al. 1991). Thomaides et al. (1989) found that turkey vulture diet in west Texas, USA, reflected the abundance of smaller taxa in their environment. Mammals (including abundant leporid remains) were detected in all pellets ($n = 91$) examined, reptiles in 83.5%, and birds in 44%. Hiraldo et al. (1991) noted a similar propensity for smaller mammal species in turkey vulture diet in northern Mexico and attributed it to competitive exclusion by the larger black vultures from larger carcasses. Prior (1990) found similar reliance upon smaller scavenged species for turkey vultures in southern Canada in an environment lacking any other species of competing vulture, so turkey vultures may focus upon smaller carrion as an evolutionary adaptation rather than competitive exclusion by larger scavenging birds. Their diet (Prior 1990:709) also included many large species, such as dog (*Canis familiaris*), horse (*Equus caballus*), cattle (*Bos taurus*), pig (*Sus scrofa*), bison (*Bison bison*), and sheep (*Ovis aries*), but smaller mammals dominated in the number of taxa exploited and the frequency with which they were detected among pellets.

Unlike other species of New World and Old World vultures, turkey vultures and the other species within the genus *Cathartes* have a highly developed sense of smell, which they use to detect their food sources (Stager 1964). Houston (1986) found that the turkey vultures he studied in Panama rely almost entirely upon their sense of smell to locate food. Recently dead carcasses were not easily located by them, with one-day old carcasses much more efficiently located. Four-day old carcasses with more advanced putrescence likely were just as locatable by the turkey vultures but generally rejected as a food source. The onset of putrescence in this tropical environment is faster than that in the temperate zone, so the available window of opportunity between a carcass being locatable by decomposition smell and its too-far advancement into decay is wider in colder climates. No significant differences were noted between the amount of time necessary to locate carcasses that were exposed on the forest floor vs. those covered with a layer of leaves and were essentially invisible from the air. Stager (1964) also found that turkey vultures could locate hidden food baits and that they were not attracted to decoy (non-food) baits meant to evoke a visual response. The preference for fresher over actively decomposing meat was confirmed using side-by-side baiting scenarios (Houston 1986). The turkey vultures were also highly efficient at locating one-day old carcasses, with 80% of $n = 24$ one-day old carcasses located in the first 12 h after placement and the remainder located the next day. Of a total of 74 baits of all types used in the study, 71 were located by the turkey vultures within three days of placement, with the remaining three being carcasses that were older at the time of placement. Excluding older carcasses, over 90% of the original bait mass (in this case domestic chickens, *Gallus gallus*) was consumed by vultures.

Black Vultures (*Coragyps atratus*)

Black vultures have black head and plumage coloration and therefore are easily distinguished from turkey vultures at close range or when viewed using remote cameras at experimental feeding stations. They overlap in size with turkey vultures and have an adult body mass around 1100–1900 g and a wingspan around 137–150 cm (Houston 2001). Black vultures range from the southern United States, wintering at least as far north as Pennsylvania, and through most of South America (Demo et al. 2013). In recent years, their summer range has been expanding farther north, including New England (Rabenold and Decker 1989), possibly in response to climate change, new sources of food/reduced competition, or reestablishment of a prior range. Coleman and Fraser (1989) measured average home ranges of black vultures in southern Pennsylvania and northern Maryland, USA, at 14,881 ha (57.5 miles^2). Coleman and Fraser (1989) found that the black vultures that they studied in western Pennsylvania spent from 9% to 12% of the day (varying seasonally) on the wing, significantly less than the turkey vultures in the same study. While almost entirely a scavenger, this species also preys upon live small vertebrates on occasion (Stager 1964).

Black vultures are more aggressive than turkey vultures and tend to dominate turkey vultures where the two feed together (Buckley 1996; Stolen 2000; Wallace and Temple 1987), but they also tend to exploit carcasses of larger species more frequently than turkey vultures (Stewart 1978). This may account for why black vultures spend less time in flight, visually searching for food, since they usually exploit larger individual carcasses once located. They also tend to fly at higher altitudes in search of food (Stolen 2000), perhaps because they rely upon sight rather than upon scent to locate food (Stager 1964) and do not have highly developed olfactory structures. Black vultures also may rely upon turkey vultures to locate food for them and follow this species to a carcass, where they then displace the less dominant turkey vultures (Stewart 1978; Wallace and Temple 1987). Black vultures may live closely with turkey vultures and often share the same roosting areas, with no segregation among the species (Yahner et al. 1990) and with overlapping home ranges (Coleman and Fraser 1989). This sympatric behavior makes dietary analysis difficult from pellet analysis, as data must often be pooled between the two species when utilizing this source.

The dietary niche of black vultures is to exploit larger vertebrate carcasses on average than are typical of turkey vultures, although a great deal of overlap occurs (Houston 2001; Kelly et al. 2007; van Dooren 2011). Stewart (1978) recorded multiple instances of cattle carcasses being fed upon by black vultures, with turkey vultures spotted in the area but never alighting on the carcasses. Reeves (2009) also recorded black vultures dominating feeding at large carcasses.

Roosting groups of black vultures can be quite large throughout the year, but nesting tends to take place in isolation. Rabenold (1987) noted a 10-day average of 238.8 individual black vultures sharing the same roosting area during winter in North Carolina, USA. When feeding, large flocks of black vultures may exploit the same resource while competing with other species (Ballejo et al. 2015). Stewart (1978) noted up to 60 black vultures congregating daily at a chicken farm, which could supply a large and reliable source of carcasses to support such a large group at once. Wallace and Temple (1987:294) noted groups of over 50 black vultures feeding at the same large carcasses at sites in Peru, with the largest group noted including 230–240 individuals of this species. Reeves (2009) noted peaks of around 30 individuals feeding on single carcasses in Texas, USA, most of which were black vultures, and Spradley et al. (2012) noted similar amounts feeding upon a single human body in Texas.

Other North American (Nearctic) Scavenging Bird Species

Multiple other avian taxa with ranges including portions of North America are common scavengers of vertebrate remains. These include crows (*Corvus* spp.), hawks and buzzards (*Buteo* spp.), some falcons (Falconidae), gulls (Laridae), and even blue jays (*Cyanocitta cristata*) and chickadees (Paridae) (Beck et al. 2015; Flint et al. 2010; Holland 1989; Jennelle et al. 2009; Komar and Beattie 1998; Montalvo and Tallade 2009; Prior and Weatherhead 1991; Roen and Yahner 2005; Schulwitz et al. 2019; Selva et al. 2005; Sorg et al. 2012; Young et al. 2014). Most of these taxa are smaller than vultures and have a lesser potential to cause taphonomic alterations to large vertebrate skeletal remains, due to their lower biting force, lower daily food intakes, and decreased ability to disperse remains around their point of initial deposition, three factors that are also important in the scale of taphonomic effects of terrestrial scavengers (see Chapter 9, this volume). While some of these species also feed in large groups (Restani et al. 2001), some are less gregarious than vultures and feed in smaller groups or singly (Dall and Wright 2009), further reducing their potential overall effect. The social dominance of vultures also may reduce the taphonomic effect of these other species if they are displaced from feeding at the same carcass.

The Family Corvidae includes the genus *Corvus* (crows, rooks, ravens, and jackdaws), which includes approximately 40 species worldwide. These include American crow (*C. brachyrhynchos*) and the common raven (*C. corax*). Blue jays are also members of the

Family Corvidae and consume carrion. Crows are broad omnivores who prey upon small species (Dall and Wright 2009; Frame 2010; Komar and Beattie 1998). They are known to eat almost anything, including garbage at landfill sites, where they are frequent pests (Baxter and Robinson 2007; Restani et al. 2001). They often include large vertebrate carrion in their diet (Badia et al. 2019; Jennelle et al. 2009). Common ravens are known to follow predatory species, including wolves (*Canis lupus*), to feed on the leftovers of their kills (Selva et al. 2005; Stahler et al. 2002). Such behavior (kleptoparasitic foraging) would allow them to arrive at carcasses on average before vultures and other species and gain a feeding advantage prior to being displaced by more dominant scavengers. Wolf feeding also allows entry through thick-skinned prey species that the ravens could not open themselves (Stahler et al. 2002). Ravens also will feed on discarded prey remains from other predatory species, including seabirds, bears, and humans (Matley et al. 2012; Restani et al. 2001). Black-billed magpies (*Pica hudsonia*) were noted preferentially to scavenge previously charred remains, stripping small (10–20 kg) experimental pig carcasses within one day (Stamper et al. 2020). Intact pigs received no attention, and unburned pigs with wounds received some scavenging, so intact skin may be a deterrent to access. A general lack of fear of humans including an increasing reliance upon human-derived scavenged food sources (Restani et al. 2001) throughout their range also may favor corvids to be one of the earliest vertebrate scavenging species to show up at human remains left in outdoor settings. While corvids do not have a highly developed olfactory apparatus and generally rely upon sight to forage for food, ravens have been demonstrated (Harriman and Berger 1986) to use smell to some degree to locate food, at least over short distances.

The specific roles that these species play in the scavenging of human remains have been little researched. Komar and Beattie (1998) noted that crows and magpies were frequent scavengers of the experimental pigs that they analyzed in an outdoor setting in Saskatchewan, Canada. Damage to soft tissue usually included triangular lesions from the beaks, and large amounts of soft tissue were consumed by these species alone. Edges of flesh exposed by feeding activity often had a cut appearance as if sliced by human action. Komar and Beattie (1998) also noted that feeding often began in areas of a carcass where soft tissue trauma had occurred, so the subsequent actions of the birds might obscure these areas of forensic interest. Asamura et al. (2004) attributed two cases of postmortem scavenging of human remains in Japan to *Corvus* through multiple lines of circumstantial evidence, including triangular defects left at the edges of feeding on soft tissue, crow footprints, and droppings nearby, sightings of large numbers of these birds in the immediate vicinity, and possible exclusion of other scavengers due to the setting. Asamura et al. (2004) found that strands of more resilient tissues (nerve fibers, tendons, and ligaments) still attached to bones often had become frayed and “fluffy,” likely due to the crows’ inability to detach these types of strongly attached tissue while feeding on more easily removed portions. In both of their cases, soft tissue loss overall was massive, although in both cases, the individual had died outdoors from burning, and other sources of postmortem tissue loss are likely.

Additional research also is required on the feeding by small birds, including songbirds (passerines). Dettling et al. (2001) described a case of postmortem epidermal skin lesions on a recently deceased individual, where the most likely culprit was a pet finch (cf. Estrildidae) in the same household. They noted that the damage accrued to the skin fit with the known pecking behavior of small birds attempting to gain moisture. Taphonomic effects in this case were confined to superficial soft tissue damage and were not found on a second deceased individual in the same house. It is also possible that small birds are

Table 16.2 **Scavenging Birds, Holliston, Massachusetts, USA**

Common Name	Taxon	Day with Contact	Night with Contact	Day no Contact	Night no Contact	Total Visits	% Total Visits
			Bird Taxa Not Detected Contacting Bone				
Great blue heron	*Ardea herodias*	0	0	2	0	2	1.7
Gray catbird	*Dumetella carolinensis*	0	0	2	0	2	1.7
Common yellowthroat	*Geothlypis trichas*	0	0	1	0	1	0.8
Black-capped chickadee	*Poecile atricapillus*	0	0	1	0	1	0.8
Common grackle	cf. *Quiscalus quiscula*	0	0	1	0	1	0.8
Common starling	cf. *Sturnus vulgaris*	0	0	2	0	2	1.7
			Bird Taxa Detected Contacting Bone				
Song sparrow	*Melospiza melodia*	0	1	26	1	28	23.3
American crow	*Corvus brachyrhynchos*	1	0	2	0	3	2.5
Dark-eyed junco	cf. *Junco hyemalis*	1	0	0	0	1	0.8
Eastern phoebe	cf. *Sayornis phoebe*	1	0	2	0	3	2.5
Robin	*Turdus migratorius*	2	0	9	0	11	9.2
Turkey vulture	*Cathartes aura*	4	0	0	0	4	3.3
House wren	*Troglodytes aedon*	4	0	18	0	22	18.3
Downy woodpecker	*Picoides pubescens*	6	0	2	0	8	6.7
Unknown Passerine		2	1	27	1	31	25.8
Totals		**21**	**2**	**95**	**2**	**120**	**100.0**

Source: Pokines and Pollock (2018:55); used with permission, *Forensic Anthropology*/University of Florida Press.

not attracted directly to the carrion but are feeding upon colonizing invertebrates (Badia et al. 2019), so studies must be designed to capture any data regarding the birds' actual feeding behavior. Pokines and Pollock (2018) examined the broader small scavenger guild, including birds and small mammals, in a largely forested area in Massachusetts, USA, using secured, isolated, fresh pig long bones. Multiple bird species were detected interacting with the bones (Table 16.2), including turkey vultures, American crow (*Corvus brachyrhynchos*), and downy woodpecker (*Picoides pubescens*), and the smaller species included song sparrow (*Melospiza melodia*), probable dark-eyed junco (cf. *Junco hyemalis*), probable eastern phoebe (cf. *Sayornis phoebe*), robin (*Turdus migratorius*), house wren (*Troglodytes aedon*), and multiple other unidentified Passerines. Previous taphonomic research at the same location recorded scavenging by black vultures, red-tailed hawk (*Buteo jamaicensis*), and great horned owl (*Bubo virginianus*) (Junod 2013; Ricketts 2012). Additional avian scavenging and dispersal research is ongoing.

Direct Damage to Bone by Large Scavenging Birds

Scavenging birds also may leave distinctive damage patterns upon bone while manipulating and consuming associated soft tissue (Ballejo et al. 2015; Hamilton and Spradley 2011; Reeves 2009; Spradley et al. 2012). Vultures have powerful beaks used to *flense* soft tissue from bone (i.e., strip the meat away while leaving the bones behind). Studies involving extant birds species scavenging humans and other large vertebrates confirm this pattern (Domínguez-Solera and Domínguez-Rodrigo 2011; Reeves 2009). Reeves (2009) found two types of markings left behind on pig and goat carcasses from (primarily black) vulture feeding: relatively shallow, irregular linear scratches up to 4 cm in length found most frequently on the skulls and less frequently on scapulae, ribs, long bones, and vertebrae, and very shallow surface scratches mostly visible as a color change on the bone surface. Scratches of the latter type were ephemeral and may be lost easily through further manipulation or environmental factors. These scratches may have been caused by beaks directly during feeding or by talons while holding food for feeding. Other large raptor species leave similar marks (Figure 16.1). Dabbs and Martin (2013), however, noted no characteristic markings from black vulture feeding experiments upon pig carcasses in Illinois, USA. Reeves (2009) noted that more telling direct signs of vulture feeding include their droppings on and around the skeletal remains, trampling of grass, and feathers left behind.

Large raptors typically hunt their own prey items rather than scavenge, but there are cases where they have opted for the latter (Gargett 1990). In cases where the raptor has

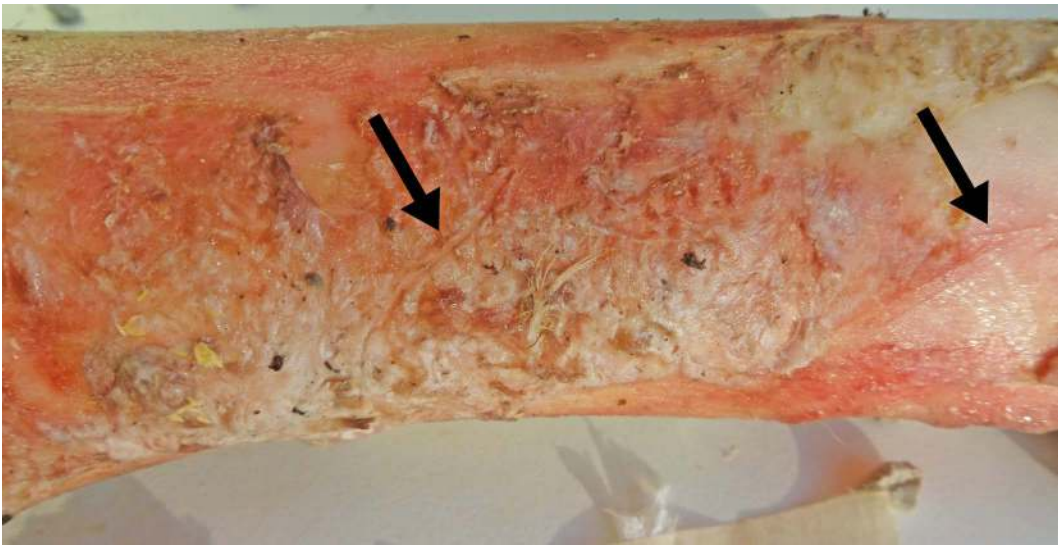

Figure 16.1 Surface striations to cattle (*Bos taurus*) long bone caused by captive, rehabilitating female bald eagle (*Haliaeetus leucocephalus*) feeding. The scoring penetrates through the adhering soft tissue (left arrow) and into the bone surface (right arrow). (Data and image courtesy of Jessie Paolello, Conservancy of Southwest Florida, Naples, FL.)

Figure 16.2 (a) Characteristic punctate depressions on the medial surface of two bovid scapulae left by an African tawny eagle (*Aquila rapax*). Note that the punctures are through the denser section of the bone, illustrating the ability of the large raptors to modify mammal skeletons larger than humans. Also note the characteristic triangular puncture left by beak piercings. (b) Composite raptor activity on a bovid scapula blade showing V-shaped nicks, scratches, and beak punctures. The scales are in cm.

overestimated the mass of its chosen prey, it will disarticulate choice elements such as the skull or a hind limb for transport back to the nest or feeding perch (Baker 2012; Berger and Clarke 1995; Gargett 1990; McGraw et al. 2006). In cases of predatory raptor feeding, puncture damage to bone (Figure 16.2) also has been noted (Baker 2012; Bocheński et al. 2009; Bocheński and Tornberg 2003), especially on prey taxa that are too large to be consumed whole and must be dismembered and/or flensed. Damage to large mammal skeletons often is confined to areas of thin bone cortex, including portions of the face, scapula blades, and long bone diaphyses (McGraw et al. 2006). Typical skull damage on primates (Figure 16.3) are scratches around the orbits, circular talon punctures through eye orbits (to access the eye), V-shaped punctures from the beak along the cranial vault resulting from the removal of the scalp, and breaks through the zygomatic arch and respective maxillary to access the tongue. Sometimes, the occipital is removed to gain access to the braincase. Komar and Beattie (1998) found that even scavenging corvids can puncture thin cortical bone and leave behind conical-shaped marks in the cancellous bone of large vertebrate bones. This type of feeding may have been to access maggots feeding in these areas.

More taphonomically exotic are the actions of bearded vultures (*Gypaetus barbatus*) upon bone. This Old World species carries bones into the air to drop them on rocks far below in order to break them open to feed on the bone fragments and marrow contents (Margalida and Bertran 2001), especially the fat reserves of adult mammals (Margalida 2008). It also swallows bone fragments, and its digestive system may cause surface alterations to bone (Houston and Copsey 1994; Margalida 2008; Margalida and Bertran 2001; Marín Arroyo and Margalida 2012; Robert and Vigne 2002). This adaptation may allow it to exist in higher altitude environments with more dispersed food resources, since bones and their digestible components (protein and fat) can survive for months or longer in a usable state, long after exterior soft tissue has been consumed or decomposed. They also may be responsible for some archaeological accumulations across their formerly much broader Old World range (Marín Arroyo et al. 2009; Robert and Vigne 2002).

Figure 16.3 A vervet monkey (*Chlorocebus pygerythrus*) cranium showing a circular puncture, possibly from a talon pressing though the skull, along with punctures of the right orbit floor. Large raptors have the potential to produce similar damage to human crania. The scale is in cm.

Potential Estimation of the PMI

Feeding rates of large numbers of scavenging birds potentially may allow an estimate of the PMI, provided that it is known that they were the primary scavenging species involved with soft tissue consumption. A relative paucity of competing terrestrial scavengers that might disperse remains or reduce the amount of soft tissue more quickly, therefore, is necessary for meaningful PMI estimates, as well as an arid or semiarid (i.e., desiccating) or freezing environment that would limit the amount of tissue loss to maggot consumption. In practical terms, these factors may limit the application to outdoor cases early in the PMI. The amount of time necessary for scavenging birds to locate a set of remains also must be considered, as must be the time of day that a body is introduced to the environment. Vultures are diurnal and stop feeding at dusk until the next morning, when they often return to the same food source from the previous day. An understanding of the potential involvement of scavenging birds (and other species) in the skeletonization process of human remains must be known if the overall rate of skeletonization (presumably from maggot and other invertebrate feeding alone) is to be used to estimate the PMI (Megyesi et al. 2005) in a given environment. Losses of large amounts of soft tissue from unknown amounts of vertebrate scavenging would greatly increase the apparent PMI estimate if it were assumed that the bulk of soft tissue loss were due to the actions of invertebrates alone.

Reeves (2009), in her experiments exposing pig and goat carcasses to vulture feeding in an enclosed area that prevented large terrestrial scavenger access, noted a typical interval of over 24 h after the time of death of the individual before the arrival of the first vultures. The amount of time between death and placement of the carcass outdoors included 2, 18, and 24 h delays, and the time of day of placement also varied. The first vultures located the carcasses in as little as 7.5 h after placement (for a carcass dead 24 h already). Other trials required 8.5 h after placement (for a carcass dead 18 h already), 24 h (dead 2 h already), and 36 h (dead 2 h already). It is unknown if the vultures would eventually reduce their carcass location time if continually baited in the same location, but other habitual artificial food sources are known to receive more constant vulture attention (Hamilton and Spradley 2011; Stewart 1978). As indicated earlier, a certain delay in finding food by turkey vultures is to be expected, given their reliance upon smell to locate decaying remains. Even where black vultures first descend upon a carcass, they in some cases may be following the locating behavior of turkey vultures. The results of Reeves (2009) follow closely those of Houston (1986) (described above) for turkey vultures to locate carcass baits placed outdoors in Panama, where an initial decomposition period of 24 h was necessary for olfactory reasons. The amount of time necessary for vultures to locate a carcass, however, included a very long delay in the experiment performed by Spradley et al. (2012) using a human cadaver in the same environment in Texas used by Reeves (2009). A single unclothed female body was not fed upon by black vultures until during the first week after placement, with only minor damage to soft tissue accrued at that time. Feeding in earnest did not ensue until 37 days after placement, then proceeded rapidly. Areas with winter snow preserving and hiding bodies also may include delays between body deposition and active feeding. Given the large differences in the time of feeding onset between these two experiments, additional research may elucidate clearer patterns in vulture behavior.

Vultures skeletonizing a set of remains, once these are located and a large number of feeding birds has arrived, may proceed very rapidly (Figure 16.4). Reeves (2009) noted typical flocks of 30 vultures skeletonizing her test carcasses (ranging in mass from 27 to 63 kg) within 48–96 h after death. The time spent actively feeding, however, was much less than these amounts: the amount of active feeding time necessary to skeletonize remains ranged from 2 h and 39 min to 26 h and 45 min. In contrast, an enclosed (i.e., eliminating vulture access) 45-kg pig control carcass took over 2 weeks to skeletonize in the same environment during a trial run concurrently with a vulture feeding trial. The drying and hardening of skin may decrease the ease of vulture access and increase the amount of time necessary to skeletonize a set of remains. Dabbs and Martin (2013), however, found much slower rates of pig carcass utilization in Illinois, USA. Initial black vulture arrival took as long as 28 days, and skeletonization took seven days to two months.

Spradley et al. (2012) noted that their human test cadaver, once located, was skeletonized over a 24 h period that included around 5 h of active vulture feeding. Other researchers similarly have noted the rapidity at which vultures can feed (Houston 1986, 2001; Prior and Weatherhead 1991; Roen and Yahner 2005; van Dooren 2011). The rapidity may increase in regions where multiple species of vulture are in competition over the same food sources (Wallace and Temple 1987). Since vulture species are in decline in some portions of the world due to losses of habitat, suitable food sources, and accidental ingestion of poisonous

Figure 16.4 Black vultures (*Coragyps atratus*; all dark plumage) with some intermixed turkey vultures (*Cathartes aura*; paler/red head plumage) feeding on a large pig (*Sus scrofa*) carcass. The second image was taken 25 min after the first, and the third image was taken 43 min after the second. Note the rapidity of soft tissue loss. (Data and images courtesy of Nicole Reeves.)

substances fed or injected into livestock (van Dooren 2011), estimates of feeding rates must take into account local population densities (Ogada et al. 2012).

Feeding rates for other scavenging bird taxa are less well known. Komar and Beattie (1998) noted that the hindquarters of an 80 kg experimentally deposited pig were consumed by the feeding of magpies alone, over the course of 1 week, with scavenging continuing over the course of a month. In this case, colder autumn weather subdued maggot activity and allowed continued access to remains.

Dispersal of Remains by Scavenging Birds

The feeding behavior of large scavenging birds also may disperse human remains around the site of deposition, especially due to the large number of birds that often feed simultaneously and the interspecies and intraspecies competition (Table 16.3). These factors

Table 16.3 Some Reported Maximum Bone Dispersal Distances by Scavenging Avian Taxa

Dispersing Taxa	Dispersed Taxa	Maximum Dispersal Distances/Context	Source
Coragyps atratus	*Homo sapiens*	Maximum distance between body parts 15.8 m, with a total area of dispersal of 83.6 m^2; experimental deposition in Texas, USA.	Spradley et al. (2012)
Coragyps atratus, *Cathartes aura*; small mammals	*Homo sapiens*	43.6 feet (13.3 m) for a skull, much dispersal of other elements; experimental deposition in Texas, USA.	Moss (2012)
Coragyps atratus	*Sus scrofa*	Up to 20 m, cranium up to 10 m; experimental pig carcasses in Illinois, USA.	Dabbs and Martin (2013)
Coragyps atratus, *Cathartes aura*; also canids and other taxa	*Sus scrofa*	>25 m for experimental juvenile pigs in the Sonoran Desert, AZ, USA.	Beck et al. (2015)
Coragyps atratus, *Cathartes aura*	*Sus scrofa*, *Capra hircus*	Multiple meters, with patterned disarticulation; experimental pig and goat carcasses in Texas, USA.	Reeves (2009)
Pica pica	*Sus scrofa*	Dispersed a rib and metatarsal to a nest 600 m distant; experimental pig carcasses in Alberta, Canada.	Komar and Beattie (1998)
Coragyps atratus	*Sus scrofa*	Up to 6 m; experimental pig carcasses in Brazil.	Demo et al. (2013)
Coragyps atratus, *Cathartes aura*, some *Haliaeetus leucocephalus*	*Sus scrofa*	Up to 15 m, majority within 6 m; experimental pig carcasses in Florida, USA.	Schultz and Mitchell (2018)
Vultur gryphus, *Coragyps atratus*, *Caracara plancus*, *Milvago chimango*	*Ovis aries*	Up to 31.6 m, experimental juvenile and adult sheep carcasses in Patagonia, Argentina. One whole adult sheep carcass moved 7 m; mean dispersal for adult sheep remains was 6.47 m.	Ballejo et al. (2015)
Cathartes aura	*Sigmodon hispidus*, *Siren* sp.	Up to 100 m; moving scavenged food items. One item had a mass of 79 g.	Stolen (2003)

are known to increase the amount of osseous dispersal caused by terrestrial scavengers (Chapter 9). Less dominant individuals may have no choice other than to grab edible portions and retreat a safe distance from the main food concentration or risk losing this food to more dominant individuals of their own or other species. Separating soft tissue from bones also may alter their original positions, as will the burrowing into a body to access portions that are easier to feed upon, especially where desiccated skin impedes feeding on soft tissue closer to the surface. Given the scavenging birds' ability to reach tight spots within and between bones with their long, sharp beaks, it is not surprising that a great deal of skeletal element manipulation and movement is typical as soft tissue is exploited more fully than that is possible without direct damage to the bones (as is typical of scavenging carnivores; Chapter 9). Once separated, individual elements may be acted upon by precipitation and gravity and dispersed even further around the area of initial deposition. Birds, regardless of their small size, should not be ignored as a potential source of osseous dispersal even among large vertebrate food sources.

Reeves (2009) noted the ability of black vultures to carry small skeletal elements in their beaks, including elements at least as large as adult goat scapulae. Other elements were observed to be carried short distances, including pig vertebrae, and displacement outside of the fenced area included a pig scapula, radius, and ulna. Other localized dispersal of elements was found to be routine in her experimentation with large vertebrate carcasses. The mandible often was detached first, followed in order by the cranium, the front limb elements, and the hind limb elements. Spradley et al. (2012) specifically examined the spatial patterning over time of human remains scavenged primarily by black vultures in Texas, USA. They found a maximum linear displacement between body parts of 15.8 m, with a total area of dispersal of 83.6 m^2. Terrain effects may account for some of this dispersal, as minor variations in local topography were noted. Much skeletal element movement was detected in between mapping dates, so continued feeding even after the main bout of skeletonization has occurred can continue to displace elements around the deposition area. Moss (2012) noted that vultures and small mammals dispersed a human cranium up to 13.3 m during experimental exposure in Texas. Komar and Beattie (1998) found that corvids were capable of dispersing small bones or fragments around a carcass feeding site in Alberta, Canada, and that some small bones including a rib and pig metatarsal were transported to a magpie nest 600 m distant. Demo et al. (2013) noted that black vultures during a feeding experiment in Brazil dispersed pig bones up to 6 m away from their point of initial deposition; Dabbs and Martin (2013) noted that black vultures dispersed pig bones during a feeding experiment in Illinois, USA, up to 20 m, including a cranium up to 10 m. Schultz and Mitchell (2018) found similar results for experimental pigs exposed in Florida, USA, where turkey and black vultures and bald eagle (*Haliaeetus leucocephalus*) dispersed remains up to 15 m. Ballejo et al. (2015) found multiple species of avian scavenger (Andean condor [*Vultur gryphus*], black vultures, and caracaras [*Caracara plancus* and *Milvago chimango*]) in Patagonia, Argentina to disperse sheep (*Ovis aries*) elements up to 31.6 m (a juvenile sheep scapula). One whole adult sheep carcass was moved 7 m prior to secondary dispersal (see Chapter 9), and the mean dispersal distance for adult sheep remains was 6.47 m.

The ability of birds to reach a carcass by air, with no passage over the ground leaving visible marks leading up to the carcass nor a large body mass in some cases to leave footprints or other traces upon landing, may account for the small amount of skeletal dispersal encountered on remains that bear no signs of terrestrial scavengers (Chapter 9). Shed feathers and droppings may indicate the previous presence of avian scavengers (Asamura et al. 2004; Reeves 2009; Stamper et al. 2020). The minor amounts of osseous dispersal caused by the migration of the maggot mass during advanced decomposition also account for the movement of smaller elements short distances (pers. obs.). Stolen (2003) also noted instances of turkey vultures transporting small scavenged food items in their beaks for up to 100 m before alighting to continue feeding. This behavior has the potential to disperse smaller human remains far past the immediate feeding area, where they are unlikely to be located later even with intensive searches. Turkey vultures have even been noted to exhume shallowly buried mammal remains for consumption, apparently detecting them through their decomposition scent alone (Smith et al. 2002). Ballejo et al. (2015) found that the original carcass location impacted subsequent bone alteration and dispersal patterns by New World vultures and caracaras in Patagonia, Argentina (see above). Carcasses in open-air sites tended to be medium to large vertebrates, and their associated scavenging raptor taphonomy was characterized by complete, fractured, scratched, notched, and punctured elements. Alternatively, smaller vertebrates that frequent rock shelter or cave sites exhibited greater overall damage including broken, corroded, fractured, and digested elements. Small disturbances to recent, shallow human burials, therefore, cannot be assumed to be the result of terrestrial scavengers alone.

Since vulture species also regurgitate pellets with the indigestible remnants of prey (Kelly et al. 2007), small consumed bones or fragments could be dispersed from the point of feeding in this manner. Turkey vultures and black vultures congregate in communal roosts, so it is possible, though largely uninvestigated, that highly fragmentary, digestively eroded (Houston and Copsey 1994) osseous remains could be concentrated in these areas (Thomaides et al. 1989; Yahner et al. 1990). Multiple species of Old World vulture frequently reconcentrate bones at their roosting sites to a far greater degree and in a more identifiable state (Plug 1978), sometimes as a result of provisioning juveniles (Mundy and Ledger 1976). Multiple crow species also *cache* food, removing it from its source and hiding it in other locations for later consumption (Bugnyar et al. 2007; Heinrich and Pepper 1998). Caching is also practiced among some species of terrestrial carnivore (Chapter 9). This behavior among crows has the potential to disperse small human bones/fragments away from their place of initial deposition, and they are unlikely to be recovered once removed and hidden in this manner.

Conclusions

While taphonomic alteration of smaller primate remains by large raptor predation is common, including extant monkey taxa and in at least one case (the Taung Child) the extinct hominin species *Australopithecus africanus*, such alteration to modern human remains is generally not a factor in forensic investigations. While large raptors do damage bone during predation, feeding, and transport, far more likely is the taphonomic alteration of human remains by avian scavengers, which feed on a wide range of vertebrate carcasses. In North America, the most ubiquitous of these are the turkey vulture and black vulture – two wide-ranging and common species that evolved to exploit carrion efficiently. Their adaptations include the ability to locate fresh remains within their home ranges and a feeding apparatus to exploit these food sources when encountered. The introduction of human remains into their environment represents an important food source, and feeding upon these remains can leave distinctive direct alterations to bone surfaces and cause the dispersal of bone away from the point of initial deposition. While not as overall destructive and dispersive as some of the large terrestrial scavengers inhabiting North America (Chapter 9), the potential for feeding by vultures and smaller avian scavengers (including crows and blue jays) is an important taphonomic consideration that cannot be overlooked in rural, outdoor crime scenes. Such feeding may occur in suburban areas close to human habitations as well (pers. obs.). Avian scavengers also have access to locations that exclude large terrestrial scavengers, sometimes by specific design as in the case of fenced outdoor decomposition facilities used for forensic taphonomic experimentation (Reeves 2009; Ricketts 2012). Recent advances in our knowledge of the taphonomic effects that these taxa have upon large vertebrates in the New World (Hamilton and Spradley 2011; Komar and Beattie 1998; Moss 2012; Pokines and Pollock 2018; Reeves 2009; Schultz and Mitchell 2018 Spradley et al. 2012; Stamper et al. 2020) and Old World (De Ruiter et al. 2010; Domínguez-Solera and Domínguez-Rodrigo 2011; Margalida 2008; Margalida and

Bertran 2001; Marín Arroyo and Margalida 2012) are important steps that should be followed up with additional research programs geared toward these species.

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References

Andrews, P. (1990) *Owls, Caves and Fossils*. University of Chicago Press, Chicago.

Armstrong, A., and G. Avery (2014) Taphonomy of Verreaux's eagle (*Aquila verreauxii*) prey accumulations from the Cape Floral Region, South Africa: Implications for archaeological interpretations. *Journal of Archaeological Science* 52:163–183.

Asamura, H., K. Takayanagi, M. Ota, K. Kobayashi, and H. Fukushima (2004) Unusual characteristic patterns of postmortem injuries. *Journal of Forensic Sciences* 49(3):592–594.

Badia, R., S. M. J. G. Steyaert, S. Puliti, R. Blaalid, and S. C. Frank (2019) Reindeer carcasses provide foraging habitat for insectivorous birds of the alpine tundra. *Ornis Norvegica* 42:36–40.

Baker, S. E. (2012) *Accumulation Behaviours and Taphonomic Signatures of Extant Verreaux's Eagles,* Aquila verreauxii, *in Southern Africa*. M.A. Dissertation, University of the Witwatersrand, Johannesburg, South Africa.

Ballejo, F., F. J. Fernández, C. I. Montalvo, and L. J. M. De Santis (2015) Taphonomy and dispersion of bones scavenged by New World vultures and caracaras in Northwestern Patagonia: Implications for the formation of archaeological sites. *Archaeological and Anthropological Sciences* 8(2):305–315.

Baxter, A. T., and A. P. Robinson (2007) A comparison of scavenging bird deterrence techniques at UK landfill sites. *International Journal of Pest Management* 53(4):347–356.

Beck, J., I. Ostericher, G. Sollish, and J. De León (2015) Animal scavenging and scattering and the implications for documenting the deaths of undocumented border crossers in the Sonoran Desert. *Journal of Forensic Sciences* 60(S1):S11–S20.

Berger, L. R. (2006) Predatory bird damage to the Taung type-skull of *Australopithecus africanus* Dart 1925. *American Journal of Physical Anthropology* 131(2):166–168.

Berger, L. R., and R. J. Clarke (1995) Eagle involvement in accumulation of the Taung child fauna. *Journal of Human Evolution* 29(3):275–299.

Berger, L. R., and W. S. McGraw (2007) Further evidence for eagle predation of, and feeding damage on, the Taung child. *South African Journal of Science* 103(11–12):496–498.

Bocheński, Z. M., T. Tomek, R. Tornberg, and K. Wertz (2009) Distinguishing nonhuman predation on birds: Pattern of damage done by the white-tailed eagle *Haliaetus albicilla*, with comments on the punctures made by the golden eagle *Aquila chrysaetos*. *Journal of Archaeological Science* 36(1):122–129.

Bocheński, Z. M., and R. Tornberg (2003) Fragmentation and preservation of bird bones in uneaten food remains of the Gyrfalcon *Falco rusticolus*. *Journal of Archaeological Science* 30(12):1665–1671.

Buckland, W. (1823) *Reliquiae Diluvianae, or, Observations on the Organic Remains Contained in Caves, Fissures, and Diluvial Gravel, and on Other Geological Phenomena, Attesting to the Action of an Universal Deluge*. J. Murray, London.

Buckley, N. J. (1996) Food finding and the influence of information, local enhancement, and communal roosting on foraging success of North American vultures. *The Auk* 113:473–488.

Bugnyar, T., M. Stowe, and B. Heinrich (2007) The ontogeny of caching in ravens, *Corvus corax*. *Animal Behaviour* 74(4):757–767.

Bunn, D. S., A. B. Warburton, and R. D. S. Wilson (1982) *The Barn Owl*. Buteo Books, Vermillion, SD.

Coleman, J. S., and J. D. Fraser (1989) Habitat use and home ranges of black and turkey vultures. *Journal of Wildlife Management* 53(3):782–792.

Cummings, J. H., G. E. Duke, and A. A. Jegers (1976) Corrosion of bone by solutions simulating raptor gastric juice. *Journal of Raptor Research* 10(2):55–57.

Dabbs, G. R., and D. C. Martin (2013) Geographic variation in the taphonomic effect of vulture scavenging: The case for southern Illinois. *Journal of Forensic Sciences* 58(S1):S20–S25.

Dall, S. R. X., and J. Wright (2009) Rich pickings near large communal roosts favor 'gang' foraging by juvenile common ravens, *Corvus corax*. *PLoS ONE* 4:1–7. DOI: 10.1371/journal.pone.0004530.

Davis, D. H. S. (1959) The barn owl's contribution to ecology and palaeoecology. In *Proceedings of the First Pan-African Ornithological Conference* ed. by M. K. Rowan, pp. 143–153. *Ostrich*, Supplement No. 3.

De Ruiter, D. J., S. R Copeland, J. Lee-Thorp, and M. Sponheimer (2010) Investigating the role of eagles as accumulating agents in the dolomitic cave infills of South Africa. *Journal of Taphonomy* 8(1-2):129–154.

Demo, C., E. Rogério Cansi, C. Kosmann, and J. R. Pujol-Luz (2013) Vultures and others scavenger vertebrates associated with man-sized pig carcasses: A perspective in Forensic Taphonomy. *Zoologia (Curitiba)* 30(5):574–576.

Dettling, A., P. Strohbeck-Kuhner, G. Schmitt, and H. T. Haffner (2001) Tierfras durch einen Singvogel? *Archiv für Kriminologie* 208:48–53.

Dodson, P., and D. Wexlar (1979) Taphonomic investigations of owl pellets. *Paleobiology* 5(3):275–284.

Domínguez-Solera, S., and M. Domínguez-Rodrigo (2011) A taphonomic study of a carcass consumed by griffon vultures (*Gyps fulvus*) and its relevance for the interpretation of bone surface modifications. *Archaeological and Anthropological Sciences* 3(4):385–392.

Duke, G. E., A. A. Jegers, G. Loff, and O. A. Evanson (1975) Gastric digestion in some raptors. *Comparative Biochemistry and Physiology* 50A:649–656.

Flint, P. L., E. W. Lance, K. M. Sowl, and T. F. Donnelly (2010) Estimating carcass persistence and scavenging bias in a human-influenced landscape in western Alaska. *Journal of Field Ornithology* 81(2):206–214.

Frame, P. F. (2010) Observations of a possible foraging tool used by common ravens. *The Wilson Journal of Ornithology* 122(1):181–182.

Gargett, V. (1990) *The Black Eagle: A Study*. Acorn Books and Russel Friedman Books, Randburg, South Africa.

Gilbert, C. C., W. S. McGraw, and E. Delson (2009) Plio-Pleistocene eagle predation on fossil cercopithecids from the Humptata Plateau, southern Angola. *American Journal of Physical Anthropology* 139(3):421–429.

Glading, B., D. F. Tillotson, and D. M. Selleck (1943) Raptor pellets as indicators of food habits. *California Fish and Game* 29(3):92–121.

Glue, D. E. (1970) Avian predator pellet analysis and the mammalogist. *Mammal Review* 1(3): 53–62.

Gourichon, L. (2002) Bird remains from Jerf El Ahmar a PPNA site in northern Syria with special reference to the griffon vulture (*Gyps fulvus*). In *Archaeozoology of the Near East, V* ed. by H. Buitenhuis, A. M. Choyke, M. Mashkour, and A. H. Al-Shiyab, pp. 138–152. ARC-Publicaties 62, Groningen, Netherlands.

Hamilton, M. D., and M. K. Spradley (2011) Purported drug cartel use of vultures as a method for body disposal. *Journal of Forensic Identification* 61(5):425–429.

Harriman, A. E., and R. H. Berger (1986) Olfactory acuity in the common raven (*Corvus corax*). *Physiology and Behavior* 36:257–262.

Hart, D. L., and R. W. Sussman (2008) *Man the Hunted: Primates, Predators, and Human Evolution* (rev. ed.). Westview Press, Cambridge, MA.

Hart, D. L. (2000) *Primates as Prey: Ecological, Morphological, and Behavioral Relationships between Primate Species and Their Predators*. Ph.D. Dissertation, Washington University, St. Louis, MO.

Heinrich, B., and J. W. Pepper (1998) Influence of competitors on caching behaviour in the common raven, *Corvus corax*. *Animal Behaviour* 56(5):1083–1090.

Hiraldo, F., M. Delibes, and J. A. Donazar (1991) Comparison of diets of turkey vultures in three regions of northern Mexico. *Journal of Field Ornithology* 62(3):319–324.

Holland, D. C. (1989) An instance of carrion-feeding by the peregrine falcon (*Falco peregrinus*). *Journal of Raptor Research* 23(4):184.

Houlihan, P. F., and S. M. Goodman (1986) *The Birds of Ancient Egypt*. The Natural History of Egypt, Vol. 1. Aris & Phillips, Warminster, UK.

Houston, D. C. (1986) Scavenging efficiency of turkey vultures in tropical forest. *The Condor* 88:318–323.

Houston, D. C. (2001) *Condors and Vultures*. Voyager Press, Stillwater, MN.

Houston, D. C., and J. A. Copsey (1994) Bone digestion and intestinal morphology of the bearded vulture. *Journal of Raptor Research* 28(2):73–78.

Houston, C. S., P. D. McLoughlin, J. T. Mandel, M. J. Bechard, M. J. Stoffel, D. R. Barber, and K. L. Bildstein (2011) Breeding home ranges of migratory turkey vultures near their northern limit. *The Wilson Journal of Ornithology* 123(3):472–478.

Jennelle, C. S., M. D. Samuel, C. A. Nolden, and E. A. Berkley (2009) Deer carcass decomposition and potential scavenger exposure to chronic wasting disease. *Journal of Wildlife Management* 73(5):655–662.

Junod, C. A. (2013) *Subaerial Bone Weathering and Other Taphonomic Changes in a Temperate Climate*. M.S. Thesis, Boston University School of Medicine, Boston.

Kelly, N. E., D. W. Sparks, T. L. DeVault, and O. E. Rhodes, Jr. (2007) Diet of black and turkey vultures in a forested landscape. *The Wilson Journal of Ornithology* 119(2):267–270.

Kofron, C. P. (1999) Attacks to humans and domestic animals by the southern cassowary (*Casuarius casuarius johnsonii*) in Queensland, Australia. *Journal of Zoology (London)* 249:375–381.

Komar, D., and O. Beattie (1998) Identifying bird scavenging in fleshed and dry remains. *Canadian Society of Forensic Science Journal* 31(3):177–188.

Korth, W. W. (1979) Taphonomy of microvertebrate fossil assemblages. *Annals of the Carnegie Museum* 48:235–285.

Levinson, M. (1982) Taphonomy of microvertebrates from owl pellets to cave breccia. *Annals of the Transvaal Museum* 33(6):115–120.

Lloveras, L., R. Thomas, R. Lourenço, J. Caro, and A. Dias (2014) Understanding the taphonomic signature of Bonelli's Eagle (*Aquila fasciata*). *Journal of Archaeological Science* 49:455–471.

Lovari, S., A. Renzoni, and R. Fondi (1976) The predatory habits of the barn owl (*Tyto alba* Scopoli) in relation to the vegetation cover. *Bollettino de Zoologia* 43(1–2):173–191.

Lyman, R. L., E. Power, and R. J. Lyman (2003) Quantification and sampling of faunal remains in owl pellets. *Journal of Taphonomy* 1(1):3–14.

Mandel, J. T., K. L. Bildstein, G. Bohrer, and D. W. Winkler (2008) Movement ecology of migration in turkey vultures. *Proceedings of the National Academy of Sciences* 105:19102–19107.

Margalida, A. (2008) Bearded vultures (*Gypaetus barbatus*) prefer fatty bones. *Behavioral Ecology and Sociobiology* 63:187–193.

Margalida, A., and J. Bertran (2001) Function and temporal variation in the use of ossuaries by the bearded vulture (*Gypaetus barbatus*) during the nestling period. *The Auk* 118(3):785–789.

Marín Arroyo, A. B., P. Fosse, and J.-D. Vigne (2009) Probable evidences of bone accumulation by Pleistocene bearded vulture at the archaeological site of El Mirón Cave (Spain). *Journal of Archaeological Science* 36(2):284–296.

Marín Arroyo, A. B., and A. Margalida (2012) Distinguishing bearded vulture activities within archaeological contexts: Identification guidelines. *International Journal of Osteoarchaeology* 22:563–576.

Martin, D. (1996) On the cultural ecology of sky burial on the Himalayan Plateau. *East and West* 46(3–4):353–370.

Matley, J. K., R. E. Crawford, and T. A. Dick (2012) Observation of common raven (*Corvus corax*) scavenging Arctic cod (*Boreogadus saida*) from seabirds in the Canadian High Arctic. *Polar Biology* 35:1119–1122.

Mayhew, D. F. (1977) Avian predators as accumulators of fossil mammal material. *Boreas* 6:25–31.

McGraw, W. S., C. Cooke, and S. Shultz (2006) Primate remains from African crowned eagle (*Stephanoaetus coronatus*) nests in Ivory Coast's Tai Forest: Implications for primate predation and early hominid taphonomy in South Africa. *American Journal of Physical Anthropology* 131(2):151–165.

Megyesi, M. S., S. P. Nawrocki, and N. H. Haskell (2005) Using accumulated degree-days to estimate the postmortem interval from decomposed human remains. *Journal of Forensic Sciences* 50(3):618–626.

Montalvo, C. I., and P. O. Tallade (2009) Taphonomy of the accumulations produced by *Caracara plancus* (Falconidae). Analysis of prey remains and pellets. *Journal of Taphonomy* 7(2–3):235–248.

Moon, E. L. (1940) Notes on hawk and owl pellet formation and identification. *Transactions of the Kansas Academy of Science* 43:457–466.

Moss, K. E. (2012) *The Effects of Avian and Terrestrial Scavenger Activity on Human Remains and Decomposition in Southeast Texas during an 18 Month Study.* M.A. Thesis, University of Houston, Houston, TX.

Mundy, P. J., and J. A. Ledger (1976) Griffon vultures, carnivores and bones. *South African Journal of Science* 72(4):106–110.

Nock, D. B. (1932) Cremation and burial in the Roman empire. *Harvard Theological Review* 25(4):321–359.

Ogada, D. L., M. E. Torchin, M. F. Kinnaird, and V. O. Ezenwa (2012) Effects of vulture declines on facultative scavengers and potential implications for mammalian disease transmission. *Conservation Biology* 26(3):453–460.

Parker, J. W. (1999) Raptor attacks on people. *Journal of Raptor Research* 33(1):63–66.

Phillips, R. L., J. L. Cummings, G. Notah, and C. Mullis (1996) Golden eagle predation on domestic calves. *Wildlife Society Bulletin* 24(3):468–470.

Plug, I. (1978) Collecting patterns of six species of vultures (Aves: Accipitridae). *Annals of the Transvaal Museum* 31(6):51–63.

Pokines, J. T. (1998) *Paleoecology of Lower Magdalenian Cantabrian Spain*. British Archaeological Reports, International Series S713, Oxford.

Pokines, J. T., and J. Kerbis Peterhans (1998) Barn owl (*Tyto alba*) taphonomy in the Negev Desert, Israel. *Israel Journal of Zoology* 44(1):19–27.

Pokines, J. T., A. Nowell, M. S. Bisson, C. E. Cordova, and C. J. H. Ames (2011) The functioning of a natural faunal trap in a semi-arid environment: Preliminary investigations of WZM-1, a limestone sinkhole site near Wadi Zarqa Ma'in, Hashemite Kingdom of Jordan. *Journal of Taphonomy* 9(2):89–115.

Pokines, J. T., and C. Pollock (2018) The small scavenger guild of Massachusetts. *Forensic Anthropology* 1(1):52–67.

Prior, K. A. (1990) Turkey vulture food habits in southern Ontario. *The Wilson Bulletin* 102(4):706–710.

Prior, K. A., and P. J. Weatherhead (1991) Competition at the carcass: Opportunities for social foraging by turkey vultures in southern Ontario. *Canadian Journal of Zoology* 69(6):1550–1556.

Rabenold, P. P. (1987) Roost attendance and aggression in black vultures. *The Auk* 104(4):647–653.

Rabenold, P. P., and M. D. Decker (1989) Black and turkey vultures expand their ranges northward. *Eyas* 2:11–15.

Reed, D. N. (2005) Taphonomic implications of roosting behavior and trophic habits in two species of African owl. *Journal of Archaeological Science* 32(11):1669–1676.

Reed, E. B. (1957) Mammal remains in pellets of Colorado barn owls. *Journal of Mammalogy* 38(1):135–136.

Reeves, N. M. (2009) Taphonomic effects of vulture scavenging. *Journal of Forensic Sciences* 54(3):523–528.

Restani, M., J. M. Marzluff, and R. E. Yates (2001) Effects of anthropogenic food sources on movements, survivorship and sociality of common ravens in the Arctic. *Condor* 103(2):399–404.

Ricketts, D. R. (2012) *Scavenging Effects and Scattering Patterns on Porcine Carcasses in Eastern Massachusetts*. M.S. Thesis, Boston University School of Medicine, Boston.

Robert, I., and J. D. Vigne (2002) The bearded vulture (*Gypaetus barbatus*) as an accumulator of archaeological bones: Late glacial assemblages and present-day reference data in Corsica (Western Mediterranean). *Journal of Archaeological Science* 29(7):763–777.

Roen, K. T., and R. H. Yahner (2005) Behavioral responses of avian scavengers in different habitats. *Northeastern Naturalist* 12(1):103–112

Sanchis Serra, A., C. Real Margalef, J. V. Morales Pérez, M. Pérez Ripoll, C. Tormo Cuñat, Y. Carrión Marco, G. Pérez Jordá, A. Ribera Gómez, J. Bolufer Marqués, and V. Villaverde Bonilla (2014) Towards the identification of a new taphonomic agent: An analysis of bone accumulations obtained from modern Egyptian vulture (*Neophron percnopterus*) nests. *Quaternary International* 330:136–149.

Sanders, W. J., J. Trapania, and J. C. Mitanic (2003) Taphonomic aspects crowned hawk-eagle predation on monkeys. *Journal of Human Evolution* 44(1):87–105.

Schultz, J. J., and A. T. Mitchell (2018) Avian scavenging of small-sized pig carcasses in Central Florida: Utilizing GIS to analyze site variables affecting skeletal dispersal. *Journal of Forensic Sciences* 63(4):1021–1032.

Schulwitz, S. E., M. C. Griffith, and C. J. W. McClure (2019) American kestrel (*Falco sparverius*) scavenging on domestic turkey (*Meleagris gallopavo*). *Wilson Journal of Ornithology* 131(20):410–413.

Scofield, R. P., and K. W. S. Ashwell (2009) Rapid somatic expansion causes the brain to lag behind: The case of the brain and behavior of New Zealand's Haast eagle (*Harpagornis moorei*). *Journal of Vertebrate Paleontology* 29(3):637–649.

Selva, N., B. Jędrzejewska, W. Jędrzejewski, and A. Wajrak (2005) Factors affecting carcass use by a guild of scavengers in European temperate woodland. *Canadian Journal of Zoology* 83(12):1590–1601.

Smith, H. R., R. M. DeGraaf, and R. S. Miller (2002) Exhumation of food by the turkey vulture. *Journal of Raptor Research* 36(2):144–145.

Sørensen, O. J., M. Totsås, T. Solstad, and R. Rigg (2008) Predation by a golden eagle on a brown bear cub. *Ursus* 19(2):190–193.

Sorg, M. H., W. D. Haglund, J. A. Wren, and A. Collar (2012) Taphonomic impacts of small and medium-sized scavengers in northern New England. *Proceedings of the American Academy of Forensic Sciences* 18:400.

Southern, H. N. (1954) Tawny owls and their prey. *Ibis* 96(3):384–410.

Spradley, M. K., M. D. Hamilton, and A. Giordano (2012) Spatial patterning of vulture scavenged human remains. *Forensic Science International* 219:57–63.

Stager, K. E. (1964) *The Role of the Olfaction in Food Location by the Turkey Vulture* (Cathartes aura). Los Angeles County Museum Contributions to Science, No. 18.

Stahler, D., B. Heinrich, and D. Smith (2002) Common ravens, *Corvus corax*, preferentially associate with grey wolves, *Canis lupus*, as a foraging strategy in winter. *Animal Behaviour* 64(2):283–290.

Stamper, T., L. Pharr, G. S. Anderson, C. Gondor, A. Dedmon, and R. Kimsey (2020) First observation of burnt vertebrate carrion scavenging by black-billed magpies (*Pica hudsonia* [Sabine]) highlights the need to evaluate all possible scavengers at a site. *Canadian Society of Forensic Science Journal* 53(3):95–108.

Stewart, P. A. (1978) Behavioral interactions and niche separation in the black and turkey vultures. *Living Bird* 17:79–84.

Stewart, K. M., L. Leblanc, D. P. Matthiesen, and J. West (1999) Microfaunal remains from a modern east African raptor roost: Patterning and implications for fossil bone scatters. *Paleobiology* 25:483–503.

Stolen, E. D. (2000) Foraging behavior of vultures in central Florida. *Florida Field Naturalist* 28(4):173–181.

Stolen, E. D. (2003) Turkey vultures carrying carrion. *Florida Field Naturalist* 31(2):22.

Terry, R. C. (2010) On raptors and rodents: Testing the ecological fidelity and spatiotemporal resolution of cave death assemblages. *Paleobiology* 36(1):137–160.

Thomaides, C., R. Valdex, W. H. Reid, and R. J. Raitt (1989) Food habits of turkey vultures in west Texas. *Journal of Raptor Research* 23(2):42–44.

Trinkaus, K. M. (1984) Mortuary ritual and mortuary remains. *Current Anthropology* 25(5):674–679.

van Dooren, T. (2011) *Vulture*. Reaktion Books, London.

Wallace, M. P., and S. A. Temple (1987) Competitive interactions within and between species in a guild of avian scavengers. *The Auk* 104(2):190–295.

Yahner, R. H., G. L. Storm, and W. L. Thompson (1990) Winter diets of vultures in Pennsylvania and Maryland. *The Wilson Bulletin* 102(2):320–325.

Young, A., R. Stillman, M. J. Smith, and A. H. Korstjens (2014) An experimental study of vertebrate scavenging behavior in a northwest European woodland context. *Journal of Forensic Sciences* 59(5):1333–1342.

Effects of Recovery Methods

17

JAMES T. POKINES
JOAN E. BAKER

Contents

> Here they stand martyrs, slain in Cupid's wars;
> And with dead cheeks advise thee to desist
> For going on death's net, whom none resist.
>
> **—William Shakespeare**
> *Pericles,* Act I, Scene 1

> Search, seek, and know how this foul murder comes.
>
> **—William Shakespeare**
> *Romeo and Juliet,* Act V, Scene 3

Introduction

Before drawing conclusions about the overall pattern of recovery from an incomplete skeleton, the following question must be addressed: are individual bones or portions thereof missing because (1) they were destroyed and/or dispersed away prior to excavation/surface recovery or (2) the searching/excavation methods or the execution thereof failed in fully recovering the remains (Bunch 2010; Cannon 1999; Dupras et al. 2012; Freeman et al. 1998;

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Haglund and Reay 1993; Lyman 2008, 2012; Mays et al. 2012; Ozbun 2011; Payne 1972; Pokines 2000; Quitmyer 2004; Shaffer and Sanchez 1994)? Natural taphonomic processes that may destroy bones include breakdown and dissolution while buried (see Chapters 2 and 5, this volume), gnawing and consumption by animal species (Chapters 7, 9, 16, and 19), advanced subaerial weathering (Chapter 11), and thermal alteration (Chapter 14).

Inherent differences in survivability relating to bone density and structure also affect recovery (Chapter 4), as does developmental state of the individual (juvenile vs. adult). Natural taphonomic agents that may disperse bones away from an area that reasonably can be excavated or searched include water movement (Chapters 6 and 7), large scavengers (Chapters 7, 9, 16, and 19), and burrowing species (Pelletier et al. 2017). Before a natural or criminal agency of bone loss can be surmised, the effects of the overall recovery system first must be ruled out. Without an understanding of the potential of a search/excavation system to be unsuccessful in osseous and other evidence recovery, erroneous conclusions may be drawn, such as ascribing missing items to natural taphonomic forces or perimortem trauma and incorrectly interpreting forensic context and postmortem history (Ball and Bobrowsky 1987).

Clearly, the goals of a given recovery shape the meaning of recovery bias, and these goals are governed by many practical time and resource considerations (cf. Porta et al. 2013). The forensic archaeologist must decide, prior to excavation or surface search, how to secure the required amount of evidence to process the scene in accordance with established professional standards (e.g., BAFA 2017; SWGANTH 2013). The acceptable minimum must be addressed along with the practical maximum: it is entirely possible to gather too much evidence, beyond the possible storage and processing capabilities of one's agency/institution, at a level that will never be required to prosecute a case or identify a missing individual. Human remains in forensic settings pose a special problem. While maximum recovery of all surviving remains is expected (i.e., representative sampling is not the goal the way it might be in the archaeological recovery of an ancient cemetery, settlement, or cave site), the fineness of the metaphorical net cast to recover these remains is subject to change based on optimizing resources relative to constraints.

For example, in cases where time for search or recovery is limited, the available modalities of identification may be an important consideration in developing a strategy, as prioritization of some aspect of the process may be required. Political or other pressures also may call for a focus on conclusively identifying the most individuals in the least amount of time rather than complete recovery of the remains for each individual (King et al. 2006; Sledzik et al. 2009: 291; Trimble 2005). In cases of extreme fragmentation, DNA may be the primary method for individual identification (Sledzik et al. 2009: 290), and precise spatial relationships may be less critical, allowing more focus on bulk recovery. If isotopic analysis or dental identifications are particularly important in a given recovery situation or if the burial environment is such that only teeth are expected to be recovered, then a finer screening protocol may be desirable in order to maximize the recovery of teeth (Bond 2002; Foster and Nance 2002; Mays et al. 2012). In mass graves, bone articulations may provide the best linkages between elements, so a clear understanding of anatomy and documentation of spatial relationships are crucial for expediting the identification process (cf. Trimble 2005). If circumstances allow, fill from an excavation (or a block of sediment containing remains) may be transported to another location for processing (Evis et al. 2015; Fairgrieve 2008; Sledzik et al. 2009). Thus, the circumstances of deposition, ultimate goals of the recovery, and methods to be used in analysis are critical to developing an appropriate recovery strategy.

Recovery system design, therefore, will be influenced by multiple factors including available overall time, budget, pre-positioning of recovery equipment, the necessity for proper documentation of finds, availability of other specialists (including handlers with cadaver dogs, heavy machinery operators, and pilots), impending poor weather or darkness, trained recovery personnel (balanced with the simultaneous need to train additional recovery personnel for future operations), other law enforcement agencies, the needs of private citizens (landowners, etc.), and the need for a safe and functioning infrastructure by the community at large (including the need to return airport runways to operational use as soon as possible after an air crash or to demolish an unsafe building after it has been largely destroyed by a fire). Unlike most other types of archaeology, forensic archaeology also has a built-in countdown to recover remains before additional decomposition can set in, making working conditions far less pleasant and subsequent identification less possible, especially in the case of mass disasters (Randall 1991; Sledzik et al. 2009; Ubelaker et al. 1995). Forensic archaeologists in general long for more time to process their sites and must have practical systems in place for the inevitable logistical compromises that must be made (Ball and Bobrowsky 1987; Menez 2005). Mistaken interpretations of the results of these compromises as the cause of missing skeletal remains can be mitigated through a thorough understanding of the limitations of the recovery methods employed.

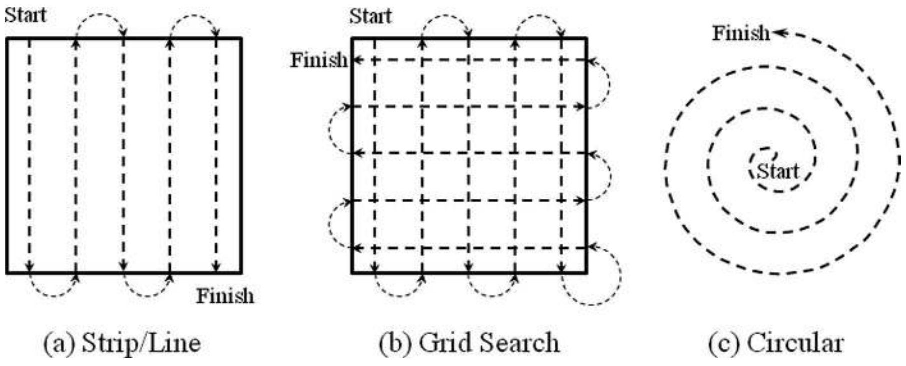
Effects of Search and Recovery Methods

Field methods for recovering human remains from terrestrial environments are split into two main categories: (1) those used to search for and recover remains on the ground surface and (2) those used to locate and recover underground remains. The problems with each are different, but both involve difficulties in *seeing* osseous remains. Many factors, including weather, terrain, size of the search area, vegetation, and efforts to conceal remains can complicate or even hinder the efforts of search teams (Kollman 2019). Surface search and recovery often require some screening of the surface decomposing humus layer and frequently are hindered by the challenges associated with finding osseous remains and associated artifacts (clothing, identification media, bullets, etc.) dispersed over a large area in potentially difficult terrain with natural obstacles (live foliage, streams, etc.). Many of the issues with locating remains during excavation arise from seeing the osseous remains, which are often stained in colors similar to the surrounding sediments. The color of bone can be a significant impediment, as the natural, unaltered color of skeletonized remains can resemble the color of dried leaf litter, or subsequent algae formation may turn it green, matching the color of foliage (Huculak and Rogers 2009; Chapter 12). This camouflage effect may decrease when bones have been bleached naturally through long-term sun exposure (Chapter 11), which might increase the amount of contrast between bones and the ground surface. Highly fragmentary remains or those covered by snow, foliage, or other types of plant litter or ground debris (e.g., trash) will be more difficult to locate. Of course, some cases may have aspects of surface search and recovery as well as excavation, such as when buried remains have been partly exhumed by scavengers, plowing, etc., and dispersed on the surface, thus marking the burial location with a surface scatter of bones. In all cases, certain procedures and equipment may help the forensic archaeologist to “see” better, and these are discussed below.

Surface Search Methods

Visual searches to locate a surface site are by their nature reliant on the ability of the searchers to recognize bones as they walk through an area (Fairgrieve 2008:62), and as such they are partially dependent upon the individual ability levels of search team members to spot bone while walking. All effective surface search methods must have in common the following components: (1) searchers must be spaced appropriately for the terrain and surface conditions so that they can cover all ground visually on a sweep without gaps between searchers; (2) swept areas must be marked visually to prevent gaps; and (3) the search area must contain all of the surface remains that can be found. The last component may be easy to determine in some cases, such as when a partial skeleton is found and searches in the surrounding area continue until all missing elements are located. The full extent of a search area only can be estimated in other cases, as the forensic anthropologist may have to presume that any missing skeletal material was consumed or dispersed beyond any reasonable search area. Agents of dispersal may include vertebrate scavengers, such as ursids, canids, and birds (Young et al. 2016; and Chapters 9 and 16), especially where remains have traces of large carnivore gnawing or bird beak/talon marks, as well as small burrowing animals, agricultural practices, and criminal activities. Even after a search team's best effort, questions may still exist regarding whether the searched area was large enough or searched thoroughly enough, and the final decision regarding cessation of search efforts will rest with the forensic archaeologist and law enforcement personnel.

Surface survey types include strip/line, grid, and circular (i.e., spiral) variations (Figure 17.1), each having the goal of maximizing the amount of ground searched visually while minimizing personnel and time (Dupras et al. 2012). Strip/line searches use multiple passes through a predetermined area. Strips or paths of travel may be individually measured off and marked to facilitate the arrangement of ground search personnel and to supply provenience for material evidence. Grid searches are similar to strip/line searches, except after the initial parallel swaths through an area, the course is shifted 90°, and the same area is covered again. This method provides redundant spatial coverage, places different sets of eyes over the same pieces of ground (assuming multiple personnel are used), and further provides the advantage of looking for evidence from different angles, maximizing shifts in lighting or surface cover that may affect visibility. Both of the first two methods are amenable to area control, as successive large rectilinear areas can be measured adjacent



(a) Strip/Line (b) Grid Search (c) Circular

Figure 17.1 Types of search patterns: (a) strip or line, (b) grid, and (c) circular (i.e., spiral). (Adapted from Dupras et al. 2012.)

to each other and searched, spreading outward from core areas to more peripheral ones. Corners can be marked temporarily and recorded using a GPS unit within known limits of accuracy. Circular searches are the most problematic, as it is inherently more difficult to guide the path of an expanding Archimedes spiral without overlapping previous rotations or straying too far outward and leaving gaps. This type of search may be used as an initial reconnaissance of an area, moving outward from a centralized bone concentration or other starting point in order to plan more thorough strip/line or grid searches covering the same ground. With all methods, items found on the initial search can be marked with pin flags for later mapping and retrieval. Combination of the search methods discussed above makes a fuller recovery more likely and allows the forensic anthropologist to assess the reason for any missing remains more reliably.

Special methods may augment the success of human search teams. Most obvious is the use of trained cadaver dog teams (Lasseter et al. 2003), which may be particularly useful not just for the initial discovery of bone concentrations and burials but also to detect widely dispersed remains, such as those dispersed along game trails by large scavengers or reconcentrated in carnivore dens (Chapter 9). Cadaver dogs, utilizing their acute sense of smell, have parallel limitations to the use of sight by searching humans. Environmental effects will alter how the scent is transmitted in the air, with such factors as wind direction and intensity, ambient temperature, and precipitation all crucial to the individual dog's success. Handler experience and fatigue of the dogs also may affect success (Lit et al. 2011). While dogs searching an area may locate scattered remains in multiple locations, one cannot say for certain that the searched areas that yielded no hits by the dogs contained zero remains any more than a negative visual search by humans in a forest covered with leaf litter indicates that no remains can be present. Other special methods of searching are geared toward finding burials and not scattered surface remains. These include probing (Owsley 1995), ground penetrating radar (Pringle et al. 2012; Schultz 2008), metal detection for associated objects (Rezos et al. 2011), and other geophysical methods (Dupras et al. 2012; Kollman 2019). Of these, metal detection is the most useful in surface searches in that it is noninvasive and may locate metal objects (rings, watches, coins, zippers, snaps, projectiles, metallic dental fillings, etc.) associated with not-yet visible skeletal remains, especially those lightly buried within the surface layer of decomposing leaf litter. Probe searches also can be effective but may damage remains and other evidence. One author (JEB) worked on a case where a secondary burial was located using a T-handled soil sampler, after one soil sample was found to include a layer with fragments of bone and leather.

Failure to recover remains may lead to other issues besides false interpretations of taphonomic history. Elements missed during the initial recovery of surface remains may be discovered after the case already has been resolved and after the previously recovered remains have been buried by next of kin. The recovery of additional remains may place an emotional burden upon surviving relatives if they have assumed closure in the aftermath of losing a loved one. Additional remains also create a resource burden for the anthropologist who likely must search the original area again, generate additional reports, and expend limited resources for DNA testing, even if no change in the previous overall analytical conclusions is necessitated by the new remains. Such issues can be avoided if a full recovery is made during the initial fieldwork.

Burned remains may be particularly difficult to locate due to heat-related changes in color, shape, and overall appearance. In general, burned bones in a human body will remain in the same relative (anatomical) position when burned unless another agent acts before, during, or after the fire to disturb the remains (Dirkmaat 2002; Fairgrieve 2008:72; Ubelaker et al. 1995; and pers. obs.). Such agents may include criminals as well as fire suppression and rescue personnel. In addition, vehicle and building fires frequently contain nonorganic materials that may be confused with human remains due to heat-related damage: plastics, plaster, foam, and insulation can all melt, warp, and discolor in ways that resemble bone (Chapter 14). Best practices require recovery of any items suspected of being bone, burned or unburned, with the final determination made under a binocular microscope in the laboratory.

Experimentation has indicated that there are differences in how detectable surface bones are during searching. Pokines et al. (2019a) tested recovery rates of isolated postcranial bones (ribs, vertebrae, metapodials, and pelves/scapulae) of white-tailed deer (*Odocoileus virginianus*) and crania of pigs (*Sus scrofa*). All bones had decomposed in the same environment previously and therefore had natural decomposition/soil staining (Pokines 2016). The bones were laid out in a forested area in two 30-x-50-m grids, one with a low amount of understory and one with moderate understory. The locations of the bones were previously randomized, and 25 bones were used per trial. Searching consisted of five searchers guided by another through the grid system, with the searchers spaced at either 1 m or 2 m intervals (i.e., searching a corridor that was 5 m wide or 10 m wide). Searching also included passing through a second time at a right angle to the first pass-through, and the searchers recorded whether the bones were found on the first or second pass-through. The overall recovery rate (Figure 17.2) for 500 total elements was 84.0% after the first pass-through with a cumulative total of 90.0% after the second pass-through. Significant differences in recovery rates were found, depending on bone type: vertebrae were recovered 70.0% of the time, with the ribs at 93.3%, metapodials at 96.7%, pelves/scapulae at 98.3%, and crania at 100.0%. The second pass-through increased all of these per-type recovery rates. No significant differences were found based upon searcher spacing or understory density. Even with tight spacing under controlled conditions in an area with known amounts and types of bone, bones similar in size and color to human bones were missed during searching. Other factors typical of real (vs. simulated) forensic site searches, including searcher inexperience and partial coverage of bones by accumulating leaf litter, would likely reduce the success rates for isolated elements. Actual forensic sites, however, may be more visible than the experimental site described above in some ways, especially where there is a concentration of bone, articulated elements, or clothing or other visible artifacts associated. Additional success also can be obtained by careful ground search after an initial concentration of remains has been located (see “Surface Processing Methods” section, below).

Initial discovery of bones, however, is often by chance. Pokines et al. (2017) examined the initial provenience of human and nonhuman skeletal cases that had been turned in to the Office of the Chief Medical Examiner, Boston, from all jurisdictions in Massachusetts and found that the majority had resulted from accidental discovery, not planned law enforcement searches. Human remains in the sample (n = 144) were most commonly found by pedestrians (47.2%), followed by unilateral turnover (10.4%), accidental excavation disturbance of unmarked burials (10.4%), fishing nets/traps (6.9%), and dog walkers/owners (6.3%), with smaller amounts discovered via police seizure, searches of buildings, and other means. Only 5.6% of the human cases were found via deliberate police search. The manners in which nonhuman cases (n = 500) were found were also dominated by pedestrians (57.0%), followed by dog walkers/owners (13.2%), other excavation (12.6%), and excavation/demolition within a residence (7.2%), with smaller amounts from other sources. Only 3.0% of the

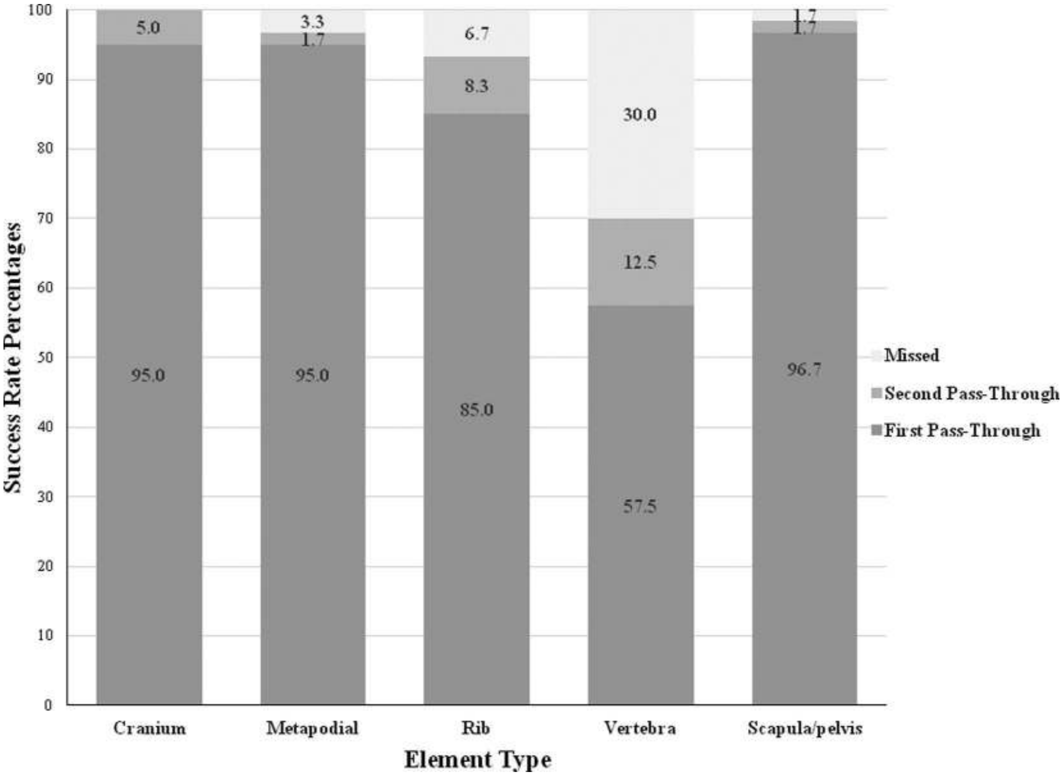


Figure 17.2 Success rates for experimental recovery of elements based upon type and number of pass-throughs for dry, naturally stained pig (*Sus scrofa*) crania and white-tailed deer (*Odocoileus virginianus*) postcranial bones in 30-x-50-m search grids, forested area with variable understory, Massachusetts, USA. Success rates varied by element type, and not even all crania were discovered on the first pass-through. (From Pokines et al. 2019a:16; used with permission, *Forensic Anthropology*/University of Florida Press.)

nonhuman cases were initially found via deliberate police search. Human and nonhuman cases had similar seasonal patterns of influx, with low amounts during winter (likely due to this location's temperate environment), a peak in late spring (corresponding with snow melt and a lack of ground cover), and high levels through the summer before decreasing in fall. General patterns of human activity may have a larger impact upon the successful finds of the skeletal remains of missing individuals than deliberate searches in this type of environment and jurisdictional (state-level) system. In contrast, Christensen and Pokines (2020) compared the provenience of a large sample (n = 136) of human and nonhuman cases examined at the FBI laboratory. A significantly higher proportion (52.9%) of FBI laboratory cases was discovered through deliberate law enforcement searches, with the remainder initiated through accidental discovery by pedestrians, hunters, hikers, voluntary turnovers, (non-cadaver) dogs, and other sources. The types of cases and regions handled by the laboratory, therefore, may have a significant impact upon the sources of cases examined.

Surface Processing Methods

Importantly, the methods used to *locate* a surface scene are not the same methods to be used to *process* that scene once it has been located. The methods described above are for broad area searching and cannot be used effectively on their own to recover surface remains, as many bones are likely to be missed. Once the site has been located, operations shift into a different mode to process any concentrated areas of remains. In addition, surface processing methods are generally too slow to use as methods of finding a site initially: teams do not normally search over a wide area of forest while crawling and sorting through every leaf in order to locate a concentration of bones. Pokines (2015) advocated an inside-out method around known concentrations of remains, first clearing all leaf litter while moving toward the concentration in order to determine its extent and completeness. Searching then reverses course and moves outwards to expand the search area, with the knowledge of which bones, if any, were not present in the concentration. All clearance involves careful (e.g., one handful at a time) sorting through leaf litter and denuding the area of any standing understory by shearing. Excavation into the surface is performed next. Mapping is completed after surface clearing so that objects hidden by leaf litter will not undergo heavy trampling in their hidden state.

The effectiveness of these surface scene processing methods has been examined experimentally, and despite careful searching, bones can be missed. Pokines et al. (2018, 2019b) performed two field experiments using the same location, a mixed forest area with sporadic understory in Massachusetts, USA. The search area was divided into ten separate 10-×-10-m units. All searching was by graduate students in an MS program in forensic anthropology, so all searchers had significant osteological training. All searching for both experiments also involved searchers crawling on their hands and knees, taking over two hours for multiple personnel to process one 10-x-10-m unit. The first experiment (Pokines et al. 2018) used pig bones comparable in size to intact human juvenile remains, partial adult remains, or intact adult remains. The recovery rates ranged from 68.1% to 81.9% per trial, with an overall recovery rate of 76.7%. The second experiment (Pokines et al. 2019b) used infant-sized bones and adult-sized teeth from pigs, with all collected leaf litter dumped onto tarps and searched a second time by additional personnel. The recovery rates from the primary search ranged from 62.4% to 74.7% per trial, with an overall rate of 68.8%. The second search through the leaves on the tarp recovered an additional 17.9% of bone (86.7% overall). Teeth were recovered through primary search at an overall rate of 38.0%, with an additional 12.0% recovered through secondary search (50.0% overall). Significant differences in recovery rate based upon bone size were detected during both experiments. The second experiment (Pokines et al. 2019b), using the same search location as the previous experiment (Pokines et al. 2018), recovered bones missed during the first experiment, boosting its overall recovery rate by 12.7%. Double-searching was clearly valuable in increasing bone recovery rates.

Excavation Methods

Multiple resources exist for training in the archaeology of skeletal recovery (Barker 1993; Blau and Ubelaker 2016; Dupras et al. 2012; Evis et al. 2015; Ferllini 2007; Ubelaker 1999), and an extensive review of methods is not possible here. The methods selected may have to be modified due to resource availability, burial characteristics, weather, or geological conditions. In addition, forensic archaeologists must choose not only the area and depth that they are excavating (i.e., the volume of sediments to be examined) but also the size of excavation grid units that will be used. In so doing, forensic archaeologists are in effect choosing the level of resolution within the site. If 4-m grid units are used, for example, and no finer control is implemented within that unit, the provenience of any object found is limited to that 16-m^2 area and within the depth range chosen. Excavators are free to subdivide larger units, at least temporarily, such as by digging this same hypothetical 16-m^2 unit in sixteen 1-m^2 subunits and recording the subunit of evidentiary items. (This process is analogous to decreasing the amount of pixilation in a digital image.) Similarly, burial features may be broken down by grid unit, and individual sediment lots are often tracked for screening with such designations as "area of right foot," "area of left hand," and "superior thoracic area," so that finds too small to be noted while excavating can be traced to a general location within the grave, relative to the skeleton. As with this anatomical area designation method, an entire block of earth containing skeletal material can be removed and returned to a laboratory for processing, saving substantial time later in the laboratory where the identification and/or siding of degraded small elements or fragments can be expedited (Evis et al. 2015).

Additional recovery methods include excavating arbitrary levels across the entire burial (once that area has been identified); dividing the burial into cranial and caudal halves and excavating each separately, with or without an intervening baulk (the "demirant excavation method"); digging equally-sized vertical slices to sterile soil (the "vertical slice method"); pedestaling of remains, which focuses on the main body mass; and the stratigraphic method (in which layers are excavated based on their depositional history and soil characteristics). Each method has advantages and disadvantages (Evis et al. 2015; Tuller and Đurić 2006). Historically, excavation methods have varied based on the archaeologist's own training and experience, which varies in part by region of the world.

Because of the lack of standardized protocols and empirical testing, little is known about error rates, factors which may have a significant effect on admissibility of evidence in court. Evis (2014) found significant disparities in the identification of material evidence and stratigraphic layers depending on the recovery method used, effects that could influence the outcome of a forensic investigation. Tuller and Đurić (2006) similarly found statistically different outcomes (in terms of small and unassociated skeletal elements) depending on recovery method. Work on recovery methods, their effects on evidence recovery, and the establishment of recovery protocols continues (Holland 2017; Kollman 2019; Moran 2019). Until protocols have been established, practitioners should familiarize themselves with and consider multiple methods, their suitability for various scenarios and conditions, and their potential shortcomings before excavating a given burial.

Underwater Search and Recovery

Underwater search and recovery operations have their own set of challenges and procedures (Green 2004). Such operations are restricted to certified dive masters with specific training in body and evidence recovery, and, in the case of disposal of fragmented or cremated remains, minimizing silt disturbance (Fairgrieve 2008). If the divers do not possess the requisite experience and training, audio and video communications to the surface with experts trained in bone recognition are essential in these operations (Fox 2003), as is the monitoring of any siphoned output for skeletal remains by trained osteologists.

The remains recovered from marine and freshwater environments in forensic cases are often fleshed, as soft tissue tends to decompose more slowly underwater than on land (Anderson 2008; Anderson and Hobischak 2002), and a large mass of fleshed remains is a much larger visual search target than individual elements. Submerged remains frequently float due to decomposition-related gas bloating (Chapters 6 and 7). Individual skeletal elements from floating remains, as they become exposed through soft tissue decomposition and scavenger feeding, frequently drop off and are dispersed, making the recovery of these isolated elements rare from any large body of water, especially the ocean. The recovery of individual skeletonized elements in underwater environments away from shipwrecks, air crashes, and other vehicles therefore is rare in forensic contexts due to the difficulty in locating them once the bones have detached from the main body of remains (with the sneaker-clad feet washing ashore in the Salish Sea area being a famous and notable exception; Engelhaupt 2021). Despite the obvious differences in operational environment, the same basic problems apply as on land: (1) visibility of skeletal elements and associated artifacts when performing underwater survey and (2) the mesh size of the screening system being sufficient to collect the remains without significant loss of elements.

Effects of Screen Mesh Size

The trade-off involved in the data gained through recovery of smaller elements with finer mesh sizes versus the greater time needed to process the sediments is one of the most fundamental methodological decisions to make on any archaeological excavation (Ball and Bobrowsky 1987). Much research exists on the effects of screen size upon bone recovery, with size classes of taxa spanning microfauna (rodents, etc.) through megafauna (cattle, horses, goats, etc.) (Cannon 1999; Freeman et al. 1998; Mays et al. 2012; Payne 1972; Pokines 2000; Shaffer and Sanchez 1994). Similarly, the effects of variable wet-screening procedures employed within the same site have been examined for macrobotanical recovery (Hosch and Zibulski 2003). Mays et al. (2012) found that by mass, a third of the remains (including bones and teeth) recovered in a series of poorly preserved inhumations were found in 4 and 8 mm screens; notably, none of the bone or dental fragments found in the 2 mm screens could be identified to element. Significantly, in these poorly preserved burials, almost 23% of the graves yielded identifiable remains only in the screened sediments (i.e., no identifiable remains were recovered in the hand-excavated sediments). Furthermore, screening of grave sediments increased recovery of human skeletal remains by 53% versus the remains recovered solely from hand excavation (Mays et al. 2012). Considering the DNA identification potential in a single tooth or bone fragment in decades-old forensic cases (Leney 2006) and the rapidity with which acidic soil can break down remains in recent contexts (Casallas and Moore 2012), screening all burial sediments is the best option, especially in contexts where bone quality is expected to be poor.

There is, however, little consensus on what constitutes a current "industry standard" for archaeological mesh size across all sites and recovery systems. Lyman (2012) noted that many authors examining osseous recovery rates based on mesh size assumed that 1/4 inch (6.4 mm) is the most popular mesh employed in large parts of the world and then compared 1/4 inch screen recovery rates with finer mesh sizes. In a sample of 25 screening method studies, 22 (88%) examined 1/4 inch mesh, 20 (80%) examined 1/8 inch (3.2 mm) mesh, and 7 (28%) examined 1/16 inch (1.6 mm) mesh. Ozbun (2011) noted the general inadequacy of 1/4 inch mesh to capture fine lithic debris and recommended 1/8 inch. James (1997) noted the prevalence of 1/4 inch screens among archaeological excavations throughout the American Southwest and Great Plains and in Mesoamerica. Forensic archaeologists receiving large parts of their broader training engaging in other types of archaeology are likely to transfer these methods to forensic settings. In the more specific world of forensic recoveries, 1/4 inch mesh is standard for all Defense POW/MIA Accounting Agency (DPAA) recovery operations (Pokines 2009), and Dupras et al. (2012) also recommended 1/4 inch mesh for the bulk of forensic recoveries, with finer mesh employed for special situations such as fetal remains. Without actual polling data from archaeologists, published professional standards for forensic archaeology (BAFA 2017; SWGANTH 2013), data culled from a suitable sample of grant reports, or sales data from archaeological mesh suppliers, the assumption that 1/4 inch mesh is employed across a large proportion of current forensic excavations is plausible but unproven.

Very fine screening systems also have been explored. For example, Freeman et al. (1998) explored wet-screening and flotation recoveries using nested screens, with the ultra-fine (nylon) mesh size at 0.25 mm, which allowed for the recovery of artifacts as small as broken bone needle tips and eyelets in large amounts from a 14,000 year old Paleolithic cave site (Freeman et al. 1998). The temporal cost involved in this type of intensive screening is high, with the time to process the sediments taking on average longer than the time to excavate them. The size of sediment lots also is a factor, as fine-screening normally involves processing of smaller individual sediment lots.

Finer mesh sizes, however, do not always translate into higher recovery rates, as finer meshes also trap larger amounts of sediment and other debris that are not relevant to the investigation (pers. obs.). If this trapped sediment obscures small bones in the screen, then the finer mesh actually decreases overall osseous recovery. The authors recommend no finer mesh than 1 mm for wet screening and 2 mm for dry screening in most forensic situations, even of fetal remains (see "Juvenile Remains" section, below). A variety of high-durability, metal-construction, nesting geological screens are available commercially (Figure 17.3) and can be used in conjunction with traditional wooden box screens with a coarser mesh for bulk processing of sediments. Wet screening is recommended for wet sediments of any kind, although delayed processing methods (where sediments are dried and then

Figure 17.3 Examples of nesting geological screens of 1 and 2 mm mesh, with even smaller sizes useful for screening special contexts such as pelvic areas of adult female skeletons when searching for suspected fetal remains. The scale is in cm.

dry-screened) are also feasible when time and resource constraints allow. This expedient solution is particularly useful where sites are far from water sources, where wet-screening equipment or personnel trained in wet-screening operations are lacking, or where insufficient time exists in the field to process burial sediments on-site. Sediments high in clay also pose a special problem in that clay adheres to bone surfaces and reduces bone visibility during sorting the contents of a screen. Wet screening in these cases may yield higher recovery rates, including the use of flocculating chemicals such as sodium hexametaphosphate (Freeman et al. 1998).

Element Size

Individual element size also is correlated with the likelihood of recovery. Due to their small size, carpals, tarsals, hand and foot sesamoids, teeth (particularly incisors or tooth fragments), epiphyses, and fetal or infant elements are some of the least likely elements to be noticed by untrained observers as well as the most likely to be overlooked during recovery. This is particularly true if the remains are not in anatomical order as in a primary burial. The results of a practical dry-screening experiment using a sample (n = 177) of modern human teeth are presented in Table 17.1. Two common mesh sizes, 1/4 inch (6.4 mm) and 1/8 inch (3.2 mm), were used to screen mixed, loose, undamaged, permanent upper and lower dentition. In order to protect the remains from damage, the teeth were not mixed with sediment, and the screens were not agitated. The purpose of screen agitation is to cause each object in the screen to present multiple aspects to the mesh openings, so that smaller objects will pass through. This can occur even if the object is only small enough in two dimensions to fit through the mesh, while the third dimension is larger (Ozbun 2011). Thus, a rib theoretically could pass through a mesh opening if its width and thickness were sufficiently small, despite its long length. Each element in the experiment was manipulated with fine forceps to determine which could pass through the mesh at any angle. This method likely overestimates the number of intact elements that would pass through the mesh during real screening operations, since several of the elements that did fit through could only do so in one orientation. These skeletal elements might get captured by the screen mesh, especially with sediments adhering. No teeth passed through the 1/8-inch mesh. The 1/4-inch mesh did not allow any of the molars, premolars, or canines to pass through, but 15 of 60 incisors (25%) could fit through. None of the incisors that passed through were maxillary central incisors. Fragments from any type of permanent tooth likely could pass through a 1/4-inch mesh, and the effects of screen mesh size on deciduous dentition or partially formed permanent tooth recovery are likely to be much greater.

Table 17.1 Screening Loss, Sample of Modern Permanent Human Teeth Passed Through 1/4 Inch (6.4 mm) Wire Mesh

Tooth Type	n =	Number Lost Through Screen	% Lost
Molar	43	0	0
Premolar	48	0	0
Canine	26	0	0
Incisor	60	15	25

Juvenile Remains

Few comparative experimental data exist for the relative recovery rates of adult versus juvenile human skeletal elements, but findings may be extrapolated from experiments with faunal remains. Shaffer (1992) and Shaffer and Sanchez (1994) found that the highest potential for recovery was with mammalian taxa above 4500 g (approximately 10 lbs.) adult body mass and that finer mesh sizes (1/8 inch/3.2 mm) significantly increased recovery rates of smaller bones. As taxon (and therefore skeletal element) body size decreased, so did relative recovery. While Mays et al. (2012) caution against extrapolating from animal remains recovery studies, the same principle holds true within a single species: remains from adult humans are much more likely to be recovered than those of human fetuses or infants (Scott 1999; Walker et al. 1988). In forensic contexts, the field recovery of fetal remains is more likely to occur in conjunction within the abdominal/pelvic area of the skeletal remains of the mother than if they occur in isolation. Alternately, juvenile remains recovery can be situational, with fetal or infant remains sometimes recovered in abundance in archaeological sites where they have been concentrated by cultural practices, such as via infanticide at the Roman site of Ashkelon in Israel (Faerman et al. 1998; Smith and Avishai 2005) or Hambleden Roman villa in England (Mays and Eyers 2011).

Pokines and De La Paz (2016) performed an experiment regarding fully skeletonized human fetal remains and their recoverability using different size meshes in a laboratory setting. Nine sets of fetal remains were used, with the youngest being approximately 18–20 weeks gestation and the oldest being approximately 40 weeks gestation, with the majority of individuals near full-term (Fazekas and Kósa 1978). Only a few partially formed deciduous tooth crowns were available. The total sample size was n = 1237, with n = 243 cranial and n = 994 postcranial elements. These were evaluated against multiple mesh sizes: 6.4 mm (1/4 inch), 3.2 mm (1/8 inch), 2.0 mm, and 1.0 mm. All remains were previously macerated, no significantly damaged or fragmentary elements were used, and no sediment was used.

The 6.4 mm mesh allowed a 63.2% overall loss of elements, including some that are diagnostic (Pokines and De La Paz 2016). These included clavicle, humerus, radius, ulna, fibula, and tibia diaphyses, large amounts of vertebrae and ribs, and all tooth crowns. The 3.2 mm mesh allowed a 16.2% overall loss of elements, including some diagnostic elements (primarily tooth crowns). The 2.0 mm mesh allowed a 7.5% overall loss of elements. The lost elements were mostly nondiagnostic (auditory ossicles, some sacral elements, ribs, metacarpals, metatarsals, third row manual phalanges, and first, second, and third row pedal phalanges), but some mostly unformed tooth crowns also were lost. The 1.0 mm mesh allowed only a 0.2% overall loss of elements, and no diagnostic elements were lost (only three third row pedal phalanges). All auditory ossicles were retained by this size mesh. The 1.0 mm mesh allowed nearly full recovery of intact fetal skeletal remains of these gestational ages, but fragmentary remains might yield a different result. Baker et al. (2005:16) recommended the use of 1.5 mm mesh for most subadult burials and 1 mm mesh for fetal and neonate burials, with nesting geological screens (Figure 17.3) expediting the process. White et al. (2012:323) and White and Folkens (2005) also recommended 1 mm mesh. Excavating *en bloc*, where the entire sediment mass that may contain the delicate skeletal material is removed as a solid mass and dissected in a controlled setting, also can be employed (Connor 2007:155) and will eliminate the potential for screening damage.

Burned Remains

Additional taphonomic events, such as burning or fragmentation, may accentuate the effect of size on recovery (Dirkmaat 2002). For example, burned teeth may shrink between 10% and 15% (Buikstra and Swegle 1989; Shipman et al. 1984). Burning also can affect recognition of skeletal material due to changes in color and/or heat-related fragmentation. Teeth may be particularly susceptible to these changes, with burning sometimes causing shattering of the enamel or complete separation of the crown from the root. If the enamel falls off of the tooth due to thermal alteration, the dentin may retain most or all of its original relief, potentially allowing identification of the tooth type, position, and size (Schmidt 2008:65). Incompletely formed teeth and mature deciduous teeth may be more susceptible to heat damage (e.g., color change and fragmentation) than mature, erupted permanent teeth, particularly if they have fallen out of their sockets (Schmidt 2008). In cases where burned remains are expected, Schmidt (2008:71) recommended screening sediment with a 1/8 inch or finer screen to ensure that all teeth and tooth fragments are recovered.

Value of Small Elements

Apart from the professional and ethical obligation to turn over as a complete set of remains as possible to the next of kin, many easily overlooked skeletal elements have analytical value. As indicated earlier, teeth may provide DNA for identification as well as an avenue for individualization through morphology and restoration patterns; they also provide valuable biological profile information including ancestry, age, sex, and childhood health. Stable isotope analysis, even of burned teeth, also may reveal the location in which an individual lived when the enamel was being formed (Ammer et al. 2020; Bartelink and Chesson 2019; Chesson et al. 2018; Font et al. 2015; Kamenov and Curtis 2017; Knudson 2008; Knudson and Buikstra 2007; Someda et al. 2016). Even the fragmentary partial crowns of perinatal remains may be analyzed for the presence of the neonatal line in order to determine if the remains are full-term fetal or post-natal (Smith and Avishai 2005), which may have important implications in forensic analyses and legal proceedings. Ríos et al. (2011) noted several of the important data that can be gathered from small skeletal elements that are frequently overlooked in situations lacking adequate screening or searching. In their excavations of a prison cemetery from the Spanish Civil War, they were able to recover large amounts of laryngeal cartilage, manual and pedal sesamoids, and medial clavicle epiphyses *in situ*. Laryngeal cartilage and sesamoids yielded information regarding relative age, perimortem trauma, and degenerative changes, while the presence of detached medial clavicle epiphyses has important implications for aging a young adult skeleton (Webb and Suchey 1985). Similarly, the easily overlooked hyoid may preserve traces of perimortem strangulation trauma (Pollanen and Chiasson 1996). Small bone fragments created during a perimortem trauma event (gunshot wound, blunt force, etc.) are especially relevant to reconstructions of the events that may have caused their fragmentation.

Field archaeologists excavating a mostly undisturbed depositional context frequently blame missing elements on the actions of small species such as rodents rather than the recovery method or lack of recognition of remains as human instead of nonhuman mammal (pers. obs.). While fossorial rodents have a high potential to disturb elements (Bocek 1992), their presence in a site often is accompanied by traces of burrows, some of which may contain their complete skeletons resulting from in-burrow mortality. Rodents do not preferentially target the smallest human skeletal elements in each hand and foot or unfused epiphyses to disturb, so lacking direct evidence of rodent involvement, the loss of these small elements is more likely to be due to excavation/screening loss or through degradation in acidic soil (Chapter 5). In addition, burrowing rodents normally displace small elements rather than destroy them, so these elements would still be present within the burial fill.

Effects of Recovery Personnel

An attentive, motivated, trained, and well-rested technician will recover more than one who is lacking in these aspects. Without personnel who can recognize, preserve, and document evidence properly, recovery efforts may be compromised or even unsuccessful (Fairgrieve 2008:61). In some international archaeological and forensic settings, local people supply much of the required field labor, including excavation and screening. Communication during training and field operations may be complicated by the fact that excavation organizers and local laborers speak different languages. In some cases, training, particularly in terms of recognition of bone and other relevant materials, may be perfunctory. For example, labor at a forensic recovery site may be supplied by individuals with varying amounts of training in recognizing skeletal material, such as sheriff's deputies, death investigators, other law enforcement personnel, morgue technicians, or forensic laboratory personnel (Fairgrieve 2008:61; Sledzik et al. 2009: 294). Training level is a particular issue when the skeletal material is isolated and fragmented (i.e., not an articulated burial). This situation can be exacerbated in mass grave situations, where a clear understanding of skeletal variation, maturation, and anatomy is crucial to segregating individuals from one another as they are recovered.

Although rarely acknowledged in the literature, fatigue is an important consideration in fieldwork in that workers who are tired are unlikely to maximize their own potential for spotting relevant items either *in situ* or in a screen mesh (Pokines et al. 2018, 2019b). Fatigue may be situational or cumulative, in that it may be related to performing a single repetitive task requiring precise focus for many hours in a single day, or it may be related to exhaustion brought on by many days of such effort. Workers in mass disaster situations, such as the World Trade Center or Pentagon recoveries, or long-term recovery efforts in stressful environments, such as mass grave excavations in wartime Iraq, may be particularly prone to cumulative fatigue (Fairgrieve 2008; Sledzik et al. 2009; pers. obs.). Emotional stress, whether personal or related to the recovery situation, and climatic conditions may exacerbate fatigue-related recovery bias. Additional factors in fatigue may be physical in origin and not directly related to the fieldwork (e.g., illness, jet lag, or drug/alcohol use).

Some studies have been performed on interobserver effects during archaeological survey. Hawkins et al. (2003) measured the success rates of multiple observers during surface survey for lithic concentrations in Cyprus and Egypt. This included analyses of the rate of lithic scatters located per hour by individual surveyors, with variations in this rate suggesting bias. In addition, linear patterns in site density were noted in Egypt, where lines of increased site density corresponded not to natural or artificial features such as rivers or settlements but rather to transects walked by individual surveyors (Hawkins et al. 2003:1505–1506). Only a weak correlation was found regarding surveyors' experience levels, and some correlation was found with specific experience in lithics. Interestingly, individual motivation may have been a factor in recovery (e.g., someone without the most experience but with a vested personal interest, such as collecting data for a doctoral dissertation, may have a higher success rate). Other factors have been found to affect the success rates of outdoor archaeological survey, including the spacing between searchers, type of object searched for, object size, and speed of searchers (Banning et al. 2006, 2011, 2017).

Effects of Recovery Setting

The environment in which recovery is conducted necessarily affects completeness of recovery. Relevant factors may include weather, lighting, and soil type. Precipitation may cause evidence to be lost through erosion or tracking of wet sediments and associated evidence away from the recovery site on workers' shoes and boots. The former may be mitigated through the use of sandbag walls or other structures to block sediment loss. The latter may be of lesser concern due to the minimal amounts of sediment typically involved, but such concerns can be addressed through setting aside a separate area for workers to collect sediment as they clean their footwear prior to leaving the site.

Lighting may play an important, but little acknowledged, role in successful recovery of evidence. For example, Banning et al. (2011) found that the results of archaeological survey differed if the searchers were walking toward or away from the sun during a given site transit. In situations where sediments may be transported from the site to a separate indoor location for processing, bright lighting may not be an issue; however, where the sole or primary location of recovery is in the field, natural lighting may influence recovery potential. Locales with high heat indices are often accompanied by bright natural lighting, but shaded processing areas are required to protect workers from heat injury. While no studies have been done to quantify the effects of lighting on recovery, common sense dictates that such considerations may play an important role in recovering skeletal remains and associated materials.

The choice of material used to provide the shade can affect visibility of evidence. For example, heat injury is a serious issue for recovery teams excavating sites in pursuit of missing US servicemembers in Southeast Asia, such as those conducted by the former Central Identification Laboratory-Hawaii, now known as the DPAA (Moore et al. 2002; Webster 1998). During the authors' tenure at these organizations, temporary shade structures were often constructed over sediment processing areas using heavy plastic tarps, usually bright blue in color. These tarps provided some relief from heat and sunlight but decreased the ambient lighting by a significant degree and often blocked any incipient breezes. The blue-tinted light also made it more difficult to see bone and other objects that had been stained red in tropical clay soil. In an attempt to moderate the amount of available lighting while maintaining air circulation, some recovery teams began using black "gardener's cloth", a type of shade netting comprising woven strips of plastic, to cover screening stations. While the strips allow both light and air through, the resulting illumination is mottled, making it difficult to discern subtle distinctions in color and shape that allow workers to distinguish evidence from organic debris and sediment. Naturally shaded areas (e.g., those located under tree cover) may present similar visibility challenges. Clearly, the question of how best to protect personnel health while maintaining maximum recovery is a complex one that deserves consideration when devising site protocols, as the very real danger of heat stroke exists under certain climatic conditions.

The effects of recovery setting may be mitigated by the transfer of sediments from a difficult field setting to a laboratory setting where sediments are screened. For example, Bunch (2010) described a process for wet-screening recovery of three sets of exhumed child remains (ages 18 months, 3 years, and 5 years) in a laboratory, where the environment and time expended could be controlled. Poor wooden coffin preservation combined with cold and rain made field conditions for recovery less than optimal. The entire coffins were removed and returned to the laboratory, and the contents underwent additional excavation and provenience recording. The two more poorly preserved sets of remains (recovered initially from a house fire) were processed with very low-pressure water and without screen agitation over 1/4 inch (6.4 mm) mesh. This gentler technique allowed the recovery of remains with signs of previous trauma, despite their delicate nature, subsequent thermal damage, and the suboptimal depositional environment. This procedure is particularly suited for forensic recoveries from coffin exhumations, where there is no real question about containment of remains within these sealed contexts and where the spatial context of individual elements is no longer critical to analysis (since these elements were not placed there as a criminal act but subsequent to any such actions). In cases where single individuals (making provenience less important) have been cremated in intense vehicle fires and where the initial recovery by law enforcement personnel lacked screening, significant additional remains may be recovered by removing the ashen debris from the vehicle interior and subsequent wet screening in a laboratory setting (pers. obs.). Burned interior components (melted plastic, foam rubber, etc.) make bone recognition in the field very difficult. Excavators also have the option to remove very delicate burned remains in the field *en bloc* so that careful, controlled recovery may occur in a laboratory setting.

Effects of Handling Procedures

Once remains have been recognized in the field, appropriate handling is essential to mitigate additional taphonomic damage (Cronyn 1990). Damp remains may be fragile and easily damaged, and mold and mildew may obscure evidence and degrade the DNA recovery potential of osseous remains. Whenever possible, remains recovered from damp settings, including many (if not most) buried remains, should be transported and stored in containers that allow moisture to evaporate. Paper bags or boxes may be used for short-term transport and storage, or desiccant packets can be used to mitigate possible damage if plastic bags are required. Further damage of burned remains during transport, storage, or analysis may reduce the identifiability of dental elements, which are especially critical to positive identification in cases where DNA potential has been destroyed by thermal alteration. Very fragile or friable remains, such as burned bone fragments or teeth, should be wrapped in cotton, tissue paper, or other soft materials to prevent damage. These items should then be placed in small hard-sided containers, such as plastic medicine bottles or film canisters, to protect them further (Fairgrieve 2008:83).

The effects of poor transport and storage procedures are akin to other destructive taphonomic processes. Bones stored in a hard container with inadequate cushioning may become crushed or fragmented, thus reducing their identifiability and obscuring their previous taphonomic history. Postmortem breakage also will reduce the amount of information in a biological profile through the loss of intact surface morphology and the number of measurements that can be taken for metric estimates of sex, age, stature, and ancestry. The destruction of a single fragile pubic bone, for example, may greatly reduce the more reliable options for sexing and aging an adult individual. In some circumstances, postmortem storage and transport damage also may be mistaken for perimortem trauma (Chapter 13),

Figure 17.4 An example of bag wear on a horse (*Equus caballus*) calcaneus that had been previously buried. The pale areas were formed on some margins as the underlying bone was exposed by rubbing against other unsecured bones in the same bag. The scale is in cm.

so minimizing this type of damage may prevent incorrect interpretations about perimortem events.

A particular type of taphonomic effect can be accrued while in storage. The taphonomic effect caused by rubbing of bones together or against the walls of their storage container is termed *bag* (or *box*) *wear* (Figure 17.4). This term likely derives from its common occurrence on bones stored in bags, as these containers permit bones to shift when the bag is moved or packed against other bags, allowing some grinding motion. Bag wear usually manifests as breakage or wear on the extremities of bones, but it can also manifest in other areas where two bones have rubbed together. Proper handling techniques will reduce the creation of this effect, but often remains are brought in for examination that have a previous history of poor storage and manipulation.

Direct Effects of Excavation upon Osseous Remains

The processes of excavation themselves may damage osseous remains in ways that mimic other taphonomic processes, including perimortem trauma. The need to move large amounts of sediment rapidly, such as in hand or mechanical trenching operations while searching for a buried body, often means that the initial discovery of remains is rather abrupt. Excavation (tool) damage is especially well known to those who have worked with skeletal remains recovered by avocational/amateur archaeologists, Works Progress Administration projects, and/or construction crews. Buried remains are often encountered accidentally by local citizens through construction work, farming activities, gardening, or digging by pets. Large amounts of damage to a skeleton may be caused at this point,

Figure 17.5 Examples of tool excavation marks on nonhuman and human bones from forensic contexts in Massachusetts, USA. Note the widths of the gouges and exposed paler underlying bone. The scales are in cm. (Upper left photograph by Jade De La Paz and Amanda Yano-Litwin; other two photographs by the authors.) The scale is in cm.

especially if remains go unnoticed while the digging proceeds and are only later recognized as significant. Recovery-related damage may result from heavy machinery such as backhoes and graders or from hand tools such as picks, shovels, and trowels, even among professional archaeologists. Examples of postmortem excavation damage from a heavy tool are shown in Figure 17.5. More delicate hand operations usually follow initial discovery and are less likely to damage remains, although poorly visualized remains are still susceptible to damage from trowels. The wood and plastic implements often used during hand excavation typically cause less damage to bone surfaces than metal ones. If the bone has become friable due to loss of organic content, a blow from a shovel can leave a deep gouge, typically a few millimeters wide and exposing underlying lighter-colored bone (Chapter 13). Friable bone also may crack at this impact site. If the gouge is large enough, the arc shape of the shovel may be visible in the gouge, leaving little doubt as to the source of the damage. These marks also may appear as lighter-colored scratches, gouges, or jagged and blocky postmortem fractures.

Conclusions

A great deal of information gleaned from a site is gained not through immediate identification of objects *in situ* but through the recovery of objects by screening individual lots of sediments. Acuity in this sense therefore is increased through improvements in screening operations, including (where needed) finer mesh sizes, wet screening of adherent sediments, and transfer of block sediments or whole exhumed coffin contents to a laboratory setting for processing. Training, motivation, and fatigue among recovery personnel may alter the recovery rates of remains and therefore the analytical conclusions drawn from them. Recovery rates may be improved through changes in the working environment, including protecting teams from sun exposure or precipitation and controlling ambient lighting to maximize the visibility of osseous remains and other evidence. Exacting recovery procedures minimize evidence loss, which in turn increases skeletal representation, completeness of biological profiles, and the identifiability of remains. Strict attention to the potential for bone loss due to possible gaps in the recovery system will prevent the assumption that natural taphonomic processes, including consumption or dispersal by large vertebrate scavengers, dissolution in acidic soil, water transport, or subaerial weathering, must have been the cause. Since the postdepositional history of skeletal remains can be recorded in many cases through their taphonomic alterations, it is incumbent upon investigators not to introduce artificial (recovery-caused) taphonomic alterations of their own. If the sources of taphonomic alterations to remains can be determined securely, the investigator may more clearly assess those that may be criminal in origin.

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References

Ammer, S. T. M., E. J. Bartelink, J. M. Vollner, B. E. Anderson, and E. M. Cunha (2020) Spatial distributions of oxygen stable isotope ratios in tap water from Mexico for region of origin predictions of unidentified border crossers. *Journal of Forensic Sciences* 65(4):1049–1055.

Anderson, G. S. (2008) *Determination of Elapsed Time since Death in Homicide Victims Disposed of in the Ocean*. Canadian Police Research Centre, Technical Report TR-102008, Ottawa, Canada.

Anderson, G. S., and N. Hobischak (2002) *Determination of Time of Death for Humans Discovered in Saltwater Using Aquatic Organism Succession and Decomposition Rates*. Canadian Police Research Centre, Technical Report TR-09-2002, Ottawa, Canada.

Baker, B. J., T. L. Dupras, M. W. Tocheri, and S. M. Wheeler (2005) *The Osteology of Infants and Children*. Texas A&M Press, College Station, TX.

Ball, B. F., and P. T. Bobrowsky (1987) Cost effectiveness and time management evaluation of intensive recovery techniques. *Canadian Journal of Archaeology* 11:75–97.

Banning, E. B., A. L. Hawkins, and S. T. Stewart (2006) Detection functions for archaeological survey. *American Antiquity* 71(4):723–742.

Banning, E. B., A. L. Hawkins, and S. T. Stewart (2011) Sweep widths and the detection of artifacts in archaeological survey. *Journal of Archaeological Science* 38(12):3447–3458.

Banning, E. B., A. L. Hawkins, S. T. Stewart, P. Hitchings, and S. Edwards (2017) Quality assurance in archaeological survey. *Journal of Archaeological Method and Theory* 24(2):466–488.

Barker, P. (1993) *Techniques of Archeological Excavation* (3rd ed.). B. T. Batsford, London.

Bartelink, E. J. and L. A. Chesson (2019) Recent applications of isotope analysis to forensic anthropology. *Forensic Science Research* 4(1):29–44.

Blau, S., and D. H. Ubelaker (eds.) (2016) *Handbook of Forensic Anthropology and Archaeology* (2nd ed.). Routledge, New York.

Bocek, B. (1992) The Jasper Ridge reexcavation experiment: Rates of artifact mixing by rodents. *American Antiquity* 57(2):261–269.

Bond, C. L., S. D. Hoyt, and E. Baxter (2002) *Archaeological Investigation Report Allen Parkway Village, 41HR886 Houston, Harris County, Texas* ed. by E. R. Foster and L. A. Nance. PBS&J, Inc., Austin, TX.

British Association of Forensic Anthropology (BAFA) (2017) Code of Practice for Forensic Anthropology. Electronic document, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/648745/Draft_Code_of_Practice_for_Anthropology_Sept_2017.pdf, accessed 27 July 2021.

Buikstra, J., and M. Swegle (1989) Bone modification due to burning: Experimental evidence. In *Bone Modification* ed. by R. Bonnichsen and M. H. Sorg, pp. 247–258. Center for Study of the First Americans, Orono, ME.

Bunch, A. W. (2010) Indoor wet screening of exhumed skeletal remains: A suggested procedure for the preparation of fragile evidence for anthropological analysis. *Journal of Forensic Sciences* 55(4):1102–1104.

Cannon, M. D. (1999) A mathematical model of the effects of screen size on zooarchaeological relative abundance measures. *Journal of Archaeological Science* 26(2):205–214.

Casallas, D. A., and M. K. Moore (2012) High soil acidity associated with near complete mineral dissolution of recently buried human remains. *Proceedings of the American Academy of Forensic Sciences* 18:400–401.

Chesson, L. A., B. J. Tipple, L. V. Youmans, M. A. O'Brien, and M. M. Harmon (2018) Forensic identification of human skeletal remains using isotopes: A brief history of applications from archaeological dig sites to modern crime scenes. In *New Perspectives in Forensic Human Skeletal Identification* ed. by K. E. Latham, E. J. Bartelink, and M. Finnegan, pp. 157–173. Academic Press, San Diego, CA.

Christensen, A. M., and J. T. Pokines (2020) Discovery context of skeletal remains received at the Federal Bureau of Investigation (FBI) Laboratory. *Forensic Anthropology* 3(1):1–5.

Connor, M. A. (2007) *Forensic Methods: Excavation for the Archaeologist and Investigator*. Altamira Press, Lanham, MD.

Cronyn, J. M. (1990) *The Elements of Archaeological Conservation*. Routledge, London.

Dirkmaat, D. C. (2002) Recovery and interpretation of the fatal fire victim: The role of forensic anthropology. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 451–472. CRC Press, Boca Raton, FL.

Dupras, T. L., J. J. Schultz, S. M. Wheeler, and L. J. Williams (2012) *Forensic Recovery of Human Remains: Archaeological Approaches* (2nd ed.). CRC Press, Boca Raton, FL.

Engelhaupt, E. (2021) How Science Solved the Mystery of Feet Washing Ashore in the Pacific Northwest. Electronic document, https://www.nationalgeographic.com/science/article/how-science-solved-the-mystery-of-feet-washing-ashore-in-the-pacific-northwest-salish-sea, accessed 27 March 2021.

Evis, L. H. (2014) *Digging the Dirt: A Comparative Analysis of Excavation Methods and Recording Systems in Relation to Their Applications in Forensic Archaeology*. Ph.D. Dissertation, Bournemouth University, UK.

Evis, L., T. Darvill, P. Cheetham, and I. Hanson (2015) Searching for a Standard: The Impact that Method Selection has on Evidence Recovery in Forensic Archaeological Investigations. Paper presented at the International Forensics Symposium, Washington DC, 22 July 2015. Electronic document, https://www.nist.gov/system/files/documents/director/method_selection_has_on_evidence_recovery_in_forensic_archaeological_investigations-evis-death-2.pdf, accessed 22 March 2021.

Faerman, M., G. Kahila Bar-Gal, D. Filon, C. L. Greenblatt, L. Stager, A. Oppenheim, and P. Smith (1998) Determining the sex of infanticide victims from the Late Roman era through ancient DNA analysis. *Journal of Archaeological Science* 25(9):861–865.

Fairgrieve, S. I. (2008) *Forensic Cremation: Recovery and Analysis*. CRC Press, Boca Raton, FL.

Fazekas, I. G., and F. Kósa (1978) *Forensic Fetal Osteology*. Akadémiai Kiadó, Budapest, Hungary.

Ferllini, R. (2007) *Forensic Archaeology and Human Rights Violations*. Charles C Thomas, Springfield, IL.

Font, L., G. Jonker, P. A. van Aalderen, E. F. Schiltmans, and G. R. Davies (2015) Provenancing of unidentified World War II casualties: Application of strontium and oxygen isotope analysis in tooth enamel. *Science and Justice* 55(1):10–17.

Foster, E., and L. A. Nance (eds.) (2002) *Archaeological Investigation Report, Allen Parkway Village, 41HR866, Houston, Harris County, TX*. Report to Housing Authority of the City of Houston, TX. PBS&J, Austin, TX.

Fox, M. (2003) Turret excavation reveals insights into ship's sinking. *Cheesebox* 13:8–11.

Freeman, L. G., J. González Echegaray, J. Pokines, H. Stettler, and M. Krupa (1998) Tamisage ultra fin et récupération de l'outillage: Observations réalisées a El Juyo (Espagne Cantabrique). *L'Anthropologie (Paris)* 102(1):35–44.

Green, J. (2004) *Maritime Archaeology: A Technical Handbook* (2nd ed.). Elsevier, San Diego, CA.

Haglund, W. D., and D. T. Reay (1993) Problems of recovering partial human remains at different times and locations: Concerns for death investigators. *Journal of Forensic Sciences* 38(1):69–80.

Hawkins, A. L., S. T. Stewart, and E. B. Banning (2003) Interobserver bias in enumerated data from archaeological survey. *Journal of Archaeological Science* 30(11):1503–1512.

Holland, T. D. (2017) Organization of Scientific Area Committees in Forensic Science [OSAC] Priority Action Report, Anthropology [Subcommittee]: Crime Scene/Death Investigation. National Institute of Standards and Technology, U.S. Department of Commerce. Electronic document, https://www.nist.gov/system/files/documents/2017/02/22/anthropology_subcommittee.pdf, accessed 22 March 2021.

Hosch, S., and P. Zibulski (2003) The influence of inconsistent wet-sieving procedures on the macroremain concentration in waterlogged sediments. *Journal of Archaeological Science* 30(7):849–857.

Huculak, M. A., and T. L. Rogers (2009) Reconstructing the sequence of events surrounding body disposition based on color staining of bone. *Journal of Forensic Sciences* 54(5):979–984.

James, S. R. (1997) Methodological issues concerning screen size recovery rates and their effects on archaeofaunal interpretations. *Journal of Archaeological Science* 24(5):385–397.

Kamenov, G. D. and J. H. Curtis (2017) Using carbon, oxygen, strontium, and lead isotopes in modern human teeth for forensic investigations: A critical overview based on data from Bulgaria. *Journal of Forensic Sciences* 62(6):1452–1459.

King, C. A., T. J. Anson, H. M. Justus, A. Fernandez-Congram, D. Siebrandt, D. Congram, M. K. Trimble. (2006) *Forensic Investigations - Commingled Remains from the NinawaA0002 Mass Grave, Ninawa Province, Iraq. Mass Graves Investigations*. US Army Corps of Engineers Mandatory Center of Expertise for the Curation and Management, St. Louis, MI.

Knudson, K. J. (2008) Tiwanaku influence in the South Central Andes: Strontium isotope analysis and Middle Horizon migration. *Latin American Antiquity* 19(1):3–23.

Knudson, K. J., and J. E. Buikstra (2007) Residential mobility and resource use in the Chiribaya polity of southern Peru: Strontium isotope analysis of archaeological tooth enamel and bone. *International Journal of Osteoarchaeology* 17(6):563–580.

Kollman, D. (2019) Hot, Cold, Above, and Below: Enhanced Survey Methods in the Detection of Clandestine Graves [abstract]. 84th Annual Meeting of the American Society for American Archeology. Electronic document, https://documents.saa.org/container/docs/default-source/doc-annualmeeting/abstract/individual-level-abstracts_final-2019-1-1.pdf?sfvrsn=5d12ea93_12, accessed 22 March 2021.

Lasseter, A. E., K. P. Jacobi, R. Farley, and L. Hensel (2003) Cadaver dog and handler team capabilities in the recovery of buried human remains in the Southeastern United States. *Journal of Forensic Sciences* 48(3):617–621.

Leney, M. D. (2006) Sampling skeletal remains for ancient DNA (aDNA): A measure of success. *Historical Archaeology* 40(3):31–49.

Lit, L., J. B. Schweitzer, and A. M. Oberbauer (2011) Handler beliefs affect scent detection dog outcomes. *Animal Cognition* 14(3):387–394.

Lyman, R. L. (2008) *Quantitative Paleozoology*. Cambridge University Press, Cambridge.

Lyman, R. L. (2012) The influence of screen mesh size, and size and shape of rodent teeth on recovery. *Journal of Archaeological Science* 39(6):1854–1861.

Mays, S., and J. Eyers (2011) Perinatal infant death at the Roman villa site at Hambleden, Buckinghamshire, England. *Journal of Archaeological Science* 38(8):1931–1938.

Mays, S., S. Vincent, and G. Campbell (2012) The value of sieving of grave soil in the recovery of human remains: An experimental study of poorly preserved archaeological inhumations. *Journal of Archaeological Science* 39(10):3248–3254.

Menez, L. L. (2005) The place of a forensic archaeologist at a crime scene involving a buried body. *Forensic Science International* 152:311–315.

Moore, C. E., II, B. D. Davis, and M. D. Leney (2002) Analysis of pilot-related equipment and archaeological strategy in the recovery of aircrew losses from the Vietnam War. *Journal of Forensic Sciences* 47(6):1210–1214.

Moran, K. (2019) Standards for Crime Scene Investigation: An OSAC Update [abstract]. 84th Annual Meeting of the American Society for American Archeology. Electronic document, https://documents.saa.org/container/docs/default-source/doc-annualmeeting/abstract/individual-level-abstracts_final-2019-1-1.pdf?sfvrsn=5d12ea93_12, accessed 22 March 2021.

Owsley, D. W. (1995) Techniques for locating burials, with emphasis on the probe. *Journal of Forensic Sciences* 40(5):735–740.

Ozbun, T. L. (2011) The inadequacy of the 1/4 inch mesh screen in archaeology. *Journal of Northwest Anthropology* 45(2):235–242.

Payne, S. (1972) Partial recovery and sample bias: The results of some sieving experiments. In: *Papers in Economic Prehistory* ed. by E. S. Higgs, pp. 49–64. Cambridge University Press, Cambridge.

Pelletier, M., A. Royer, T. W. Holliday, E. Discamps, S. Madelaine, and B. Maureille (2017) Rabbits in the grave! Consequences of bioturbation on the Neandertal "burial" at Regourdou (Montignac-sur-Vézère, Dordogne). *Journal of Human Evolution* 110:1–7.

Pokines, J. T. (2000) Microfaunal research design in the Cantabrian Spanish Paleolithic. *Journal of Anthropological Research* 56(1):95–112.

Pokines, J. T. (2009) Forensic recoveries of U.S. war dead and the effects of taphonomy and other site-altering processes. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 141–154. Prentice Hall, Upper Saddle River, NJ.

Pokines, J. T. (2015) A procedure for processing outdoor surface forensic scenes yielding skeletal remains among leaf litter. *Journal of Forensic Identification* 65(2):161–172.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T., and J. De La Paz (2016) Recovery rates of human fetal skeletal remains using varying mesh sizes. *Journal of Forensic Sciences* 61(S1):S184–S189.

Pokines, J. T., C. J. Eck, and M. E. Sharpe (2017) Sources of skeletal remains at a chief medical examiner's office: Who finds the bones? *Journal of Forensic Identification* 67(2):278–299.

Pokines, J. T., K. Mammano, M. Studebaker-Reed, J. Mowery, M. Patterson, C. Schneider, B. Trapp, and C. Mincher (2018) Success rates of recovering dispersed bones among leaf litter. *Forensic Anthropology* 1(4):189–200.

Pokines, J. T., S. Robinson, J. Mansz, N. Heidel, K. Jasny, J. Gilligan, A. Carmona, J. Kroll, S. Lavigne, and S. Calle (2019a) Success rates of forensic surface search for osseous remains in a New England, U.S.A. environment. *Forensic Anthropology* 2(1):9–20.

Pokines, J. T., M. M. Udoni, S. Sanders Stark, S. Cassidy, M. L. Atkinson, E. Church, C. L. File, M. K. Green, M. D. Herrera, G. S. Kilroy, B. N. Peace, B. J. Purcell, A. S. Reinman, A. M. Sanchez, and S. J. Springman (2019b) Success rates of recovering teeth and infant-sized bones dispersed among leaf litter. *Forensic Anthropology* 2(3):168–177.

Pollanen, M. S., and D. A. Chiasson (1996) Fracture of the hyoid bone in strangulation: Comparison of fractured and unfractured hyoids from victims of strangulation. *Journal of Forensic Sciences* 41(1):110–113.

Porta, D., P. Poppa, V. Regazzola, D. Gibelli, D. Roberta Schillaci, A. Amadasi, F. Magli, C. Cattaneo (2013) The importance of an anthropological scene of crime investigation in the case of burnt remains in vehicles: 3 case studies. *The American Journal of Forensic Medicine and Pathology* 34(3):195–200.

Pringle, J. K., J. R. Jervis, J. D. Hansen, G. M. Jones, N. J. Cassidy, and J. P. Cassella (2012) Geophysical monitoring of simulated clandestine graves using electrical and ground-penetrating radar methods: 0-3 years after burial. *Journal of Forensic Sciences* 57(6):1467–1486.

Quitmyer, I. R. (2004) What kind of data are in the back dirt? An experiment on the influence of screen size on optimal data recovery. *Archaeofauna* 13:109–129.

Randall, B. (1991) Body retrieval and morgue operation at the crash of United Flight 232. *Journal of Forensic Sciences* 36(2):403–409.

Rezos, M. M., J. J. Schultz, R. A. Murdock II, and S. A. Smith (2011) Utilizing a magnetic locator to search for buried firearms and miscellaneous weapons at a controlled research site. *Journal of Forensic Sciences* 56(5):1289–1295.

Ríos, L., A. García-Rubio, B. Martínez, C. Coch, and S. Llidó (2011) Field recovery and potential information value of small elements of the skeleton. *Homo* 62:270–279.

Schmidt, C. W. (2008) The recovery and study of burned human teeth. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. Symes, pp. 55–74. Elsevier, Amsterdam.

Schultz, J. J. (2008) Sequential monitoring of burials containing small pig cadavers using ground penetrating radar. *Journal of Forensic Sciences* 53(2):279–287.

Scientific Working Group for Forensic Anthropology (SWGANTH) (2013) Scene Detection and Processing. Electronic document, https://www.nist.gov/system/files/documents/2018/03/13/swganth_scene_detection_and_processing.pdf, accessed 23 April 2021.

Scott, E. (1999) *The Archaeology of Infancy and Infant Death*. British Archaeological Reports International Series 819, Oxford.

Shaffer, B. S. (1992) Quarter-inch screening: Understanding biases in recovery of vertebrate faunal remains. *American Antiquity* 57(1):129–136.

Shaffer, B. S., and J. L. J. Sanchez (1994) Comparison of 1/8”-and 1/4”-mesh recovery of controlled samples of small-to-medium-sized mammals. *American Antiquity* 59(3):525–530.

Shipman, P., G. Foster, and M. Schoeninger (1984) Burnt bones and teeth: An experimental study of color, morphology, crystal structure and shrinkage. *Journal of Archaeological Science* 11(4):307–325.

Sledzik, P. S., D. Dirkmaat, R. W. Mann, T. D. Holland, A. Z. Mundorff, B. J. Adams, C. M. Crowder, and F. DePaolo (2009) Disaster victim recovery and education: Forensic anthropology in the aftermath of September 11. In *Hard Evidence: Case Studies in Forensic Anthropology* (2nd ed.) ed. by D. W. Steadman, pp. 289–302. Prentice Hall, Upper Saddle River, NJ.

Smith, P., and G. Avishai (2005) The use of dental criteria for estimating postnatal survival in skeletal remains of infants. *Journal of Archaeological Science* 32(1):83–89.

Someda, H., T. Gakuhari, J. Akai, Y. Araki, T. Kodera, G. Tsumatori, Y. Kobayashi, S. Matsunaga, S. Abe, M. Hashimoto, M. Saito, M. Yoneda, and H. Ishida (2016) Trial application of oxygen and carbon isotope analysis in tooth enamel for identification of past-war victims for discriminating between Japanese and U.S. soldiers. *Forensic Science International* 261:166.e1–166.e5.

Trimble, M. K., S. A. Chomko, and C. A. Van Arsdale (2005) *Forensic Investigations at Two Mass Graves, Ninawa Province, Iraq. Mass Graves Investigation, Vol. 1.* US Army Corps of Engineers Management of Archaeological Collections, St. Louis, MO.

Tuller, H. and M. Đurić (2006) Keeping the pieces together: Comparison of mass grave excavation methodology. *Forensic Science International* 156(2–3):192–200.

Ubelaker, D. H. (1999) *Human Skeletal Remains: Excavation, Analysis, Interpretation* (3rd ed.). Taraxacum, Washington, DC.

Ubelaker, D. H., D. W. Owsley, M. M. Houck, E. Craig, W. Grant, T. Woltanski, R. Fram, K. Sandness, and N. Peerwani (1995) The role of forensic anthropology in the recovery and analysis of Branch Davidian compound victims: Recovery procedures and characteristics of the victims. *Journal of Forensic Sciences* 40(3):335–340.

Walker, P. L., J. R. Johnson, and P. M. Lambert (1988) Age and sex biases in the preservation of human skeletal remains. *American Journal of Physical Anthropology* 76(2):183–188.

Webb, P. A., and J. M. Suchey (1985) Epiphyseal union of the anterior iliac crest and medial clavicle in a modern multiracial sample of American males and females. *American Journal of Physical Anthropology* 68(4):457–466.

Webster, A. D. (1998) Excavation of a Vietnam-era aircraft crash site: Use of cross-cultural understanding and dual forensic recovery methods. *Journal of Forensic Sciences* 43(2):277–283.

White, T. D., M. T. Black, and P. A. Folkens (2012) *Human Osteology* (3rd ed.). Academic Press, Amsterdam.

White, T. D., and P. A. Folkens (2005) *The Human Bone Manual*. Academic Press, Amsterdam.

Young, A., R. Stillman, M. J. Smith, and A. H. Korstjens (2016) Applying knowledge of species-typical scavenging behavior to the search and recovery of mammalian skeletal remains. *Journal of Forensic Sciences* 61(2):458–456.

Invertebrate Modification of Bone

18

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Contents

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Introduction

The interval between death and forensic analysis is a period in which several dynamic processes are at work, the understanding and recognition of which form the primary concern of taphonomists. Essential to interpreting forensic cases is a sound understanding of the decomposition process, and a familiarity with bone modification criteria used to identify different agents. A good deal of actualistic research has been conducted in the past 40 years on the effects of large mammals, birds, and abrasion on bone. However, relatively little attention has been paid to invertebrates as agents of bone modification, which is surprising given that insects are used by forensic scientists to reconstruct length of body exposure and a subsequent sequence of events (e.g., Anderson 2001, 2010; Byrd and Castner 2001; Byrd and Tomberlin 2001; Vanin and Huchet 2017). In the current state of knowledge, five insect Orders are reported agents of bone modification: Coleoptera (beetles), Lepidoptera (moths), Blattodea (termites), Diptera (fly larvae), and Hymenoptera (ants, bees, and wasps). We summarize the damage reported for each, and add cockroaches to the Blattodea, and hide and tenebrionid beetles to the Coleoptera. We expand the list to include invertebrates in the Orders: Orthoptera (crickets), Spirostreptida (millipedes), Glomerida (pill millipedes), Isopoda (woodlice), and Gastropoda (snails).

The research presented here stems from a taphonomic analysis of *Australopithecus sediba* fossils from the Malapa site in South Africa (Berger et al. 2010). Here, two well-preserved individuals are thought to have fallen through a shaft opening to their deaths in the bottom of an underground cave (Dirks et al. 2010). Analysis of the fossils showed no evidence of rodent or carnivore damage (Val et al. 2015), features typically recorded on bones from cave sites in the area. Examination of the fossil surfaces at low magnification (10–60×) revealed, however, that the bones were modified by what appeared to be insects. Without a comparative collection of bones modified by insects at hand, this interpretation would have been founded on incomplete literature information, often only based on inferential evidence. This highlighted the need for actualistic experiments with invertebrate fauna. Bone modification experiments were conducted with 12 invertebrate taxa. Selection of the animals used was based on those known to colonize cadavers in early (flies) and late (hide beetles) stages of decomposition, and agents observed on modern skeletonized animals encountered in the field in South Africa (millipedes and "darkling" beetles) and at the Malapa site (termites and ants). Snails were included because of a taphonomic study we conducted on *Homo naledi* remains, which were discovered in mud deposits at the nearby Rising Star cave site (Berger et al. 2015; Dirks et al. 2015).

In line with the aims of this volume, our goal was to describe and illustrate the alterations to skeletal remains made by known invertebrate agents, and where possible, to differentiate between the types of damage caused by each. The taxa studied here are South African, but they have close relatives worldwide that may make similar modifications, and these too need to be explored for their taphonomic signatures on bone. This research focuses on invertebrate modification of fresh and dry bone for assisting in forensic cases. For a summary of insect damage to fossil bone, see Huchet (2014) and references therein.

Insecta

Blattodea

Termites (Isoptera)

Termites are among the most successful groups of insects on Earth, colonizing most landmasses except Antarctica. Termites mostly feed on dead plant material and cellulose, generally in the form of wood, leaf litter, soil, or animal dung. The impact of termites on modern skeletal remains has been reported by Behrensmeyer (1978), Danielson (2005, 2006); Tappen (1994), and Thorne and Kimsey (1983). Watson and Abbey (1986) conducted a termite modification of bone experiment, which stemmed from their discovery of termite damage to bones in aboriginal cave burials in Australia. Their results showed that termites favored fresh and weathered bone over fossilized material, a preference also observed on modern carcasses consumed by Neotropical termites (Thorne and Kimsey 1983). All pieces of bone used in the experiment conducted by Watson and Abbey (1986) were damaged to some extent. Most showed surface nibbling or slight attack, but substantial amounts were removed from some bones. Cancellous bone was damaged more than compact bone, and damage to compact bone was concentrated on roughened surfaces or along edges. Termite osteophagy is well known and documented (Backwell et al. 2012; Coe 1980; Derry 1911; Freymann et al. 2007; Haynes 1991; Huchet 2014, 2017; Huchet et al. 2011; Matu et al. 2017; Thorne and Kimsey 1983; Wood, 1976; Wylie et al. 1987). It remains unclear though whether termites select fresh bones for their nutrient content (lipids, nitrogen, phosphorus, calcium), or because fresh bones are rapidly colonized by the fungi that they consume. The destruction of bird bone, great extent of bone surface removal, and abrasion observed in the experimental specimens point to both. The harvesting of manganese- and iron-rich coatings from fossil surfaces is prevalent in the Malapa faunal assemblage, and is likely to harden the mandibles, as documented for the cutting edge of *Dermestes* species mandibles, which are rich in manganese and zinc (Hillerton et al. 1984).

We conducted an on-site experiment at the early hominin site of Malapa. It is in an open woodland in a grassland biome on the edge of a savanna (25°53’42’S, 27°48’05’E) in Gauteng Province, South Africa. The site is about 50 km northwest of Johannesburg, close to the town of Krugersdorp. Malapa is situated within the Cradle of Humankind World Heritage Site, which contains dolomitic caves with Plio-Pleistocene fossil deposits. Sixteen complete and fragmented bones were placed in shallow holes dug around the Malapa site, to record experimentally how the resident subterranean termites *Odontotermes badius* modify bone. The bones used in the experiment were mostly long bone shaft fragments and ribs in various stages of preservation, including fresh with tissue attached, represented by cow (*Bos taurus*) and chicken (*Gallus gallus*) bones, and dry and fossilized (*ex situ* Gladysvale deposits), represented by medium-sized mammal bone fragments and ribs. Bones used in the termite experiment ran for three months, during austral winter from May to August 2013.

Microscopic analysis revealed that bones modified by *Odontotermes badius* at the Malapa site recorded individual striations that are V-shaped with a rounded base in section, locally with a head and tail (blunt to pointed), elsewhere lens-shaped, and follow the contours of the bone (Figure 18.1a). Individual striations may occur in clusters, comprising consecutive individual sub-parallel striations on the periosteum, reminiscent of edge gnawing (Figure 18.1b). Multiple parallel striations occur as sets of shallow, approximately parallel striations that tend to cover a relatively large area (Figure 18.1c) and may overlap in distribution with surface removal and smoothing-abrasion. Pitting refers to several small and shallow pits of irregular shape found together (Figure 18.1d) and is often associated with one or two short individual striations. The Malapa termites created smooth-based pits (Figure 18.1e) and a borehole (Figure 18.1f). See Table 18.1 for definitions of terms used to describe surface modification features. Unlike mammalian carnivores that seldom, if ever, leave traces of their activity on the teeth of their prey (Chapter 9, this volume), termite modification of tooth enamel and roots is marked. Smoothing-abrasion of the surface

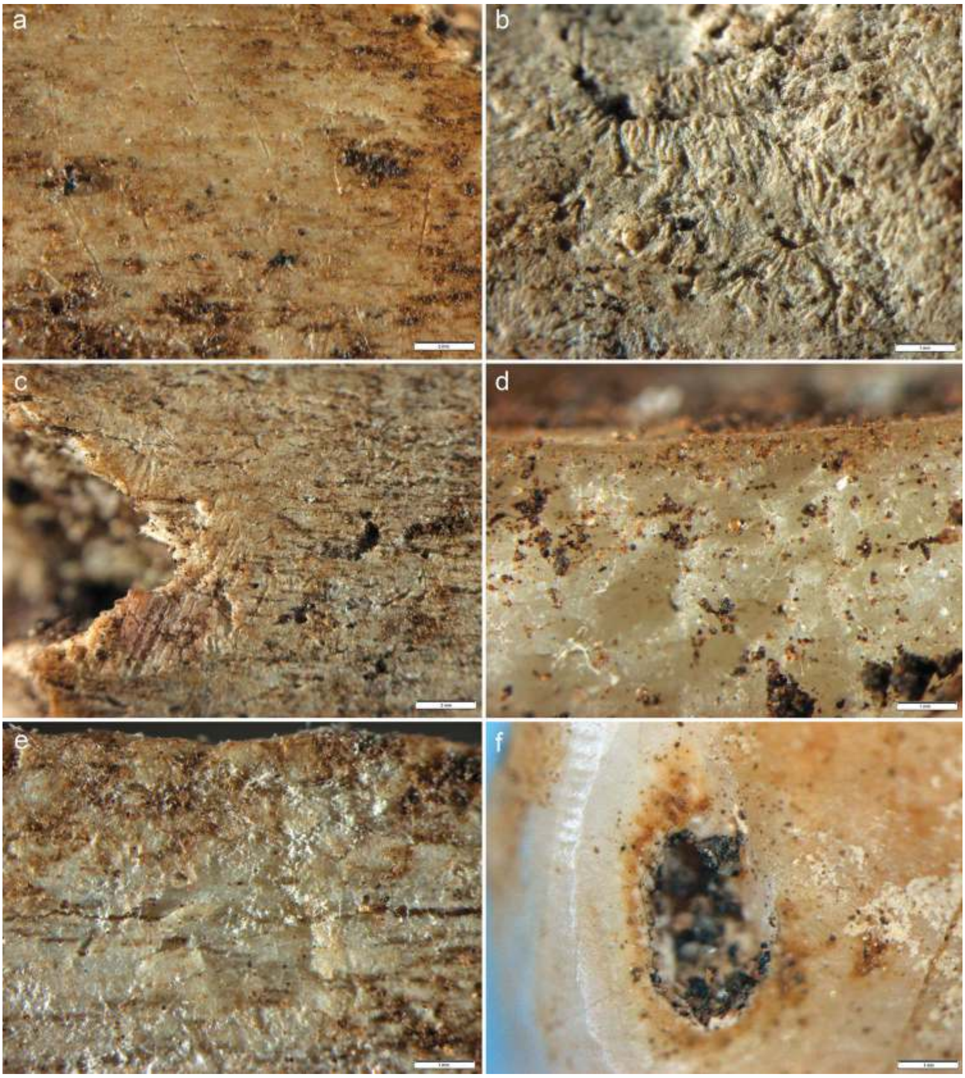

Figure 18.1 Termite (*Odontotermes badius*) damage to bones and a tooth. (a) Fine individual striations, (b) clusters of consecutive individual sub-parallel striations on a dry bone surface, (c) multiple parallel striations, (d) pitting on a fresh bone flake, (e) a smooth-based pit on a weathered bone, and (f) a borehole on the occlusal surface of a dry bovid tooth. The fine white strands and dots in (d) and (e) are remnants of fungus that has been harvested from the surfaces of the bones. Scales in a, c = 2 mm, scales in b, d, e, f = 1 mm.

may cover a relatively large area (Figure 18.2a). The termites caused an etched appearance on bone, exposing underlying bone structure (Figure 18.2b). Surface removal of the bone tends to occur over a relatively large area and was evident on most bones. It may terminate in a stepped edge where it contacts outer cortical lamellae (Figure 18.2c), or the contact may be smooth and continuous (Figure 18.2d).

Figure 18.3 shows the type of damage recorded on bones in different states of preservation. Multiple parallel striations and surface removal occurred on almost all of the bones in all states of preservation. Etching was recorded on nearly all of the fresh bones and 30% of the dry bones. Smoothing-abrasion occurred on 30% of the fresh and dry bones.

Table 18.1 **Definitions of Terms Used to Describe Microscopic Surface Modification Features Observed in This Study**

Term	Definition
Individual striations	Various forms of linear damage. Striations may be lens-shaped or have a head and a tail (blunt and pointed ends).
Multiple parallel striations	Sets of shallow, approximately parallel individual striations that tend to cover a relatively large area.
Pit with striations in the base	Roughly circular to ovoid removal of bone that results in a basin-like concavity, the base of which is scarred with individual striations, often intersecting.
Pit with a smooth base	Roughly circular to ovoid removal of bone that results in a basin-like concavity, the base of which is smooth.
Pit with emanating striae	Roughly circular to ovoid removal of bone that leaves star-shaped marks comprising individual striations radially arranged around a central point.
Pitting	A cluster of small and shallow pits of irregular shape resulting from the tips of mandibles.
Etched	Bone appears etched due to the exposure of underling vascular canals. It has the same thinned appearance as acid-etched bone.
Dissolution	Smooth-based pits and trails resulting from chemical alteration of bone or tooth.
Destruction	Obliteration of bone due to removal of a relatively large area.
Borehole	The removal of bone or tooth to produce round or ovoid holes that travel through a specimen.
Furrow	Relatively shallow U-shaped trail marks made by a biotic agent.
Smoothing-abrasion	The rounding of edges and abrasion of elevated areas to produce a smooth surface over a relatively large area.
Polish	A sheen or luster, as distinct from smoothing, which need not exhibit a sheen.
Surface removal	Removal of surface bone over a relatively large area.

Individual striations were only recorded on the dry specimens. The only borehole (large round to oval void) was on a dry tooth. Only one specimen showed no modifications, and it was a dry medium size mammal piece of cortical bone.

Compared with the modifications recorded on bones made by mound-building termites *Trinervitermes trinervoides*, called “the Snouted Harvester termite”, found in the grassland below the Malapa site (Backwell et al. 2012), *O. badius* at Malapa produced sets of multiple fine parallel striations and pitting, which the mound-builders did not. The Malapa termites did not produce any of the star-shaped marks, with individual striations stemming from a central feature such as a foramen (Figure 18.2e), nor did they produce edge gnawing (Figure 18.2f) such as that made by mound-building termites. The reason for the absence of these two features on the experimental bones used at Malapa may be that the resident termites do not make these traces, in which case the criteria that we used in the past (Backwell et al. 2012) to characterize “termite damage” are actually specific to mound-building termites (*Trinervitermes trinervoides*). Accordingly, the subterranean termites at Malapa have their own signature, and hence the criteria used to characterize termite damage are more variable than we thought. Alternatively, the absence of these features may be time-related, considering that the experiment with *O. badius* only ran for three months, when the termites were not very active, while the experiments with *T. trinervoides* ran for

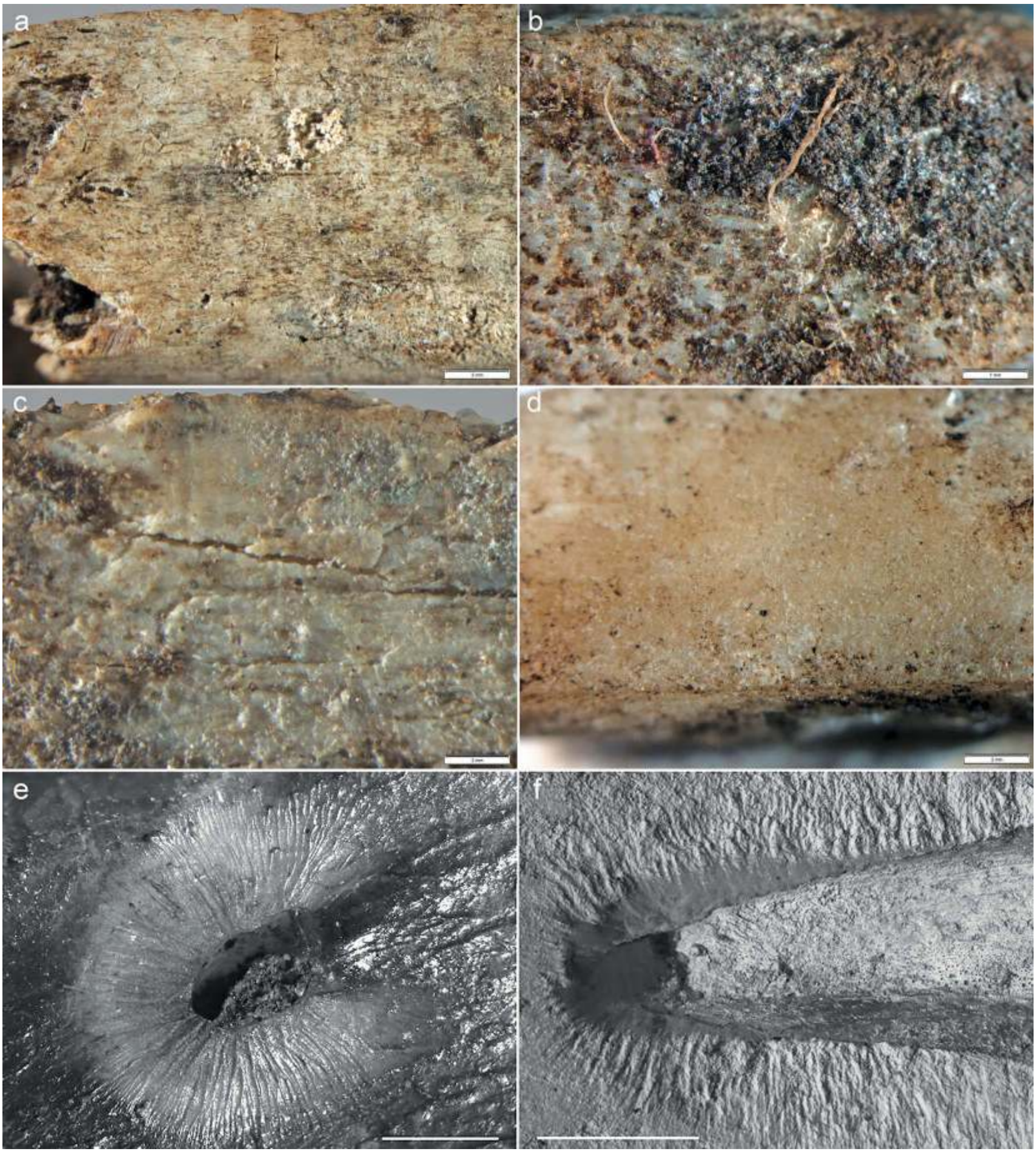

Figure 18.2 Termite damage to bone. *Odontotermes badius* from Malapa created (a) smoothing-abrasion on the surface of a weathered rib. Termites, leaving only black subsurface dendrites, removed the fungus that was on the bone, and only a small patch of fungus with a cluster of spherical mycotetes remains intact. (b) Etched surface appearance. Note the microbial strands and remnants of white fungus in the surface sediment, with black manganese deposits that formed within three months of burial. (c) Surface removal from a dry bone in a stepped manner resulting from removal of outer cortical lamellae in layers. (d) Surface removal from a fresh bone in which the transition from outer to underlying bone is smooth. The mound-building *Trinervitermes trinervoides* in the adjacent valley produced (e) star-shaped marks comprising individual striations radially arranged around a smooth-walled central cavity, and (f) edge gnawing comprising multiple approximately parallel individual striations. Scales in a, c, d = 2 mm, scale in b, e, f = 1 mm. ([e, f] Reprinted from Backwell et al. 2012:72–87, Copyright [2012], with permission from Elsevier.)

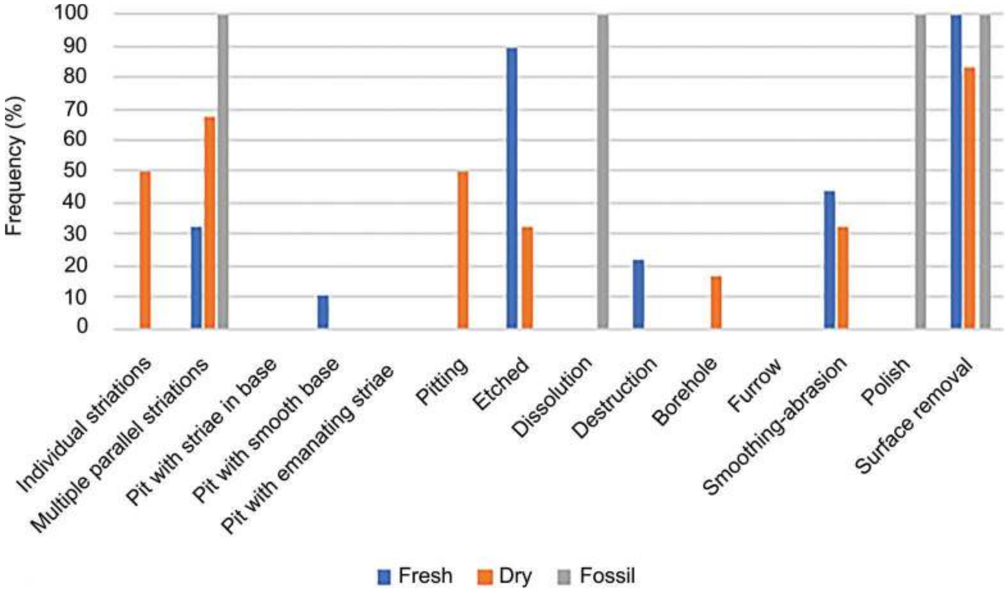

Figure 18.3 Type and frequency of damage on bone specimens in different states of preservation that were modified experimentally by *Odontotermes badius* termites at the Malapa site in South Africa. Multiple parallel striations and surface removal occurred on almost all of the bones in all states of preservation. Etching and smoothing-abrasion occurred on approximately half of the fresh and dry bone specimens.

six months and a year, at which time modifications were more pronounced. In both experiments, the matrix surrounding the bones when we retrieved them was made of carton (a mixture of fecal matter, saliva, wood fragments, and sediment used in nest construction), and it was full of galleries and tunnels. These are constructed passages and do not result from boring. No such galleries or tunnels were observed on bones in either of our experiments, but these features are documented on a human pelvis from an archaeological site in Peru where the termite *Amitermes lunae* was identified as the responsible bioagent (Huchet et al. 2011; Scheffrahn and Huchet 2010). Boring into bone was uncommon, with 12% of the mound-building termite sample of bones recording boreholes and only one specimen recording a single hole for the subterranean termites at Malapa. Hence, bones modified by termites may not exhibit traces of boring and tunneling. Both experiments showed that termites modify bones indiscriminately with regard to bone type and density and can destroy bone in all stages of preservation, favoring fresh thin cortical and cancellous bone with meat and marrow. Bone modification appears to be partly incidental, created during the process of harvesting nitrogen-rich fungus that they consume from fresh bones.

Cockroaches (Blattaria)

The order Blattoptera (Blattaria) comprises about 4000 species, divided into six families (Blaberidae, Blattellidae, Blattidae, Cryptocercidae, Nocticolidae, and Polyphagidae) (Klass and Meier 2006; Roth 2003). The majority of these species are abundant in tropical regions, but some are dependent on human habitats (e.g., *Blattella germanica*, *Periplaneta americana*, and *Blatta orientalis*) and have an extended range across all continents. The American cockroach *Periplaneta americana* is among the largest species of synanthropic cockroach and is nowadays nearly cosmopolitan. American cockroaches are native to Africa and the Middle East and were introduced to the Americas in the 17th century. Parkinson (2012) conducted a bone modification experiment using 30 individuals of this species. Eighteen bones in various states of preservation were placed in a tank with the cockroaches for six months. Results showed that they modified both fresh and dry bone, but damage was negligible. Only five of the specimens displayed signs of modification, namely minor destruction on four pieces and edge gnawing on one, comprising microscopic individual subparallel striations.

Coleoptera

Hide Beetles (Trogidae)

Adults and larvae of Trogidae beetles are primarily keratophagous and/or necrophagous and colonize carcasses during the advanced stages of postmortem decay, feeding upon scleroproteins (i.e., skin, hair, fur, horns, and hooves) and desiccated tissue such as tendons and ligaments (Palestrini et al. 1992). Our experiment showed that they readily modify fresh bone too (Backwell et al. 2020). A tank experiment was set up in the laboratory with 17 individuals of the widespread African species *Afromorgus squalidus* on inert palm peat (Starke Ayres® Palm Peat growing medium). A set of 17 bones, mostly long bone shaft fragments and ribs in various stages of preservation, including fresh with tissue attached, represented by cow and chicken bones, and dry and fossilized, represented by medium sized mammal bone fragments and ribs, were placed in the tank with the beetles. Bones used in the trogid beetle experiment ran from January to May 2012 (austral summer into winter). After four months, the bones used in the experiment showed that the beetles produced microscopic individual striations that are V-shaped with a rounded base in section, sometimes with a head and other times lens-shaped, following the contours of the bone (Figure 18.4a). They may be shallow and narrow or deep and broad (Figure 18.4b). They produced multiple fine parallel striations (Figure 18.4c), that tend to cover a relatively large area, often in association with smoothing-abrasion. They made pits with smooth bases (Figure 18.4d), pits with striations in the base (Figure 18.4e), and pits with emanating striae. Beetles pitted the surfaces of bones (Figure 18.4f) and etched them (Figure 18.5a). They destroyed bone (Figure 18.5b) and made boreholes, created smoothing and abrasion (Figure 18.5a), and removed bone surfaces (Figure 18.5c, d). Trogid beetles produced extensive and invasive edge gnawing (Figure 18.5e) reminiscent of small rodent damage (Chapter 9), but without a flat trough at the base. Edge gnawing comprised consecutive parallel individual striations, with rounded V-shapes in section. Invasive edge gnawing is the only feature that distinguishes beetle from termite damage. Even though the beetle experiment was conducted with inert palm peat, the bones almost immediately grew airborne fungal colonies, which were harvested by the beetles (Figure 18.5f). Compared to termites, trogid beetles produced more than twice as many individual striations, and about the same number of multiple fine parallel striations. Trogid beetles caused double the amount of destruction as *O. badius* termites and produced more boreholes. Both beetles and termites frequently removed bone surfaces, but beetle modification resulted in less smoothing and abrasion. Figure 18.6 shows the type of damage observed on bones in different states of preservation. Except for more etching observed on dry bones and half the amount of destruction than on fresh bones, approximately the same types of damage are recorded in similar frequencies on fresh and dry bones.

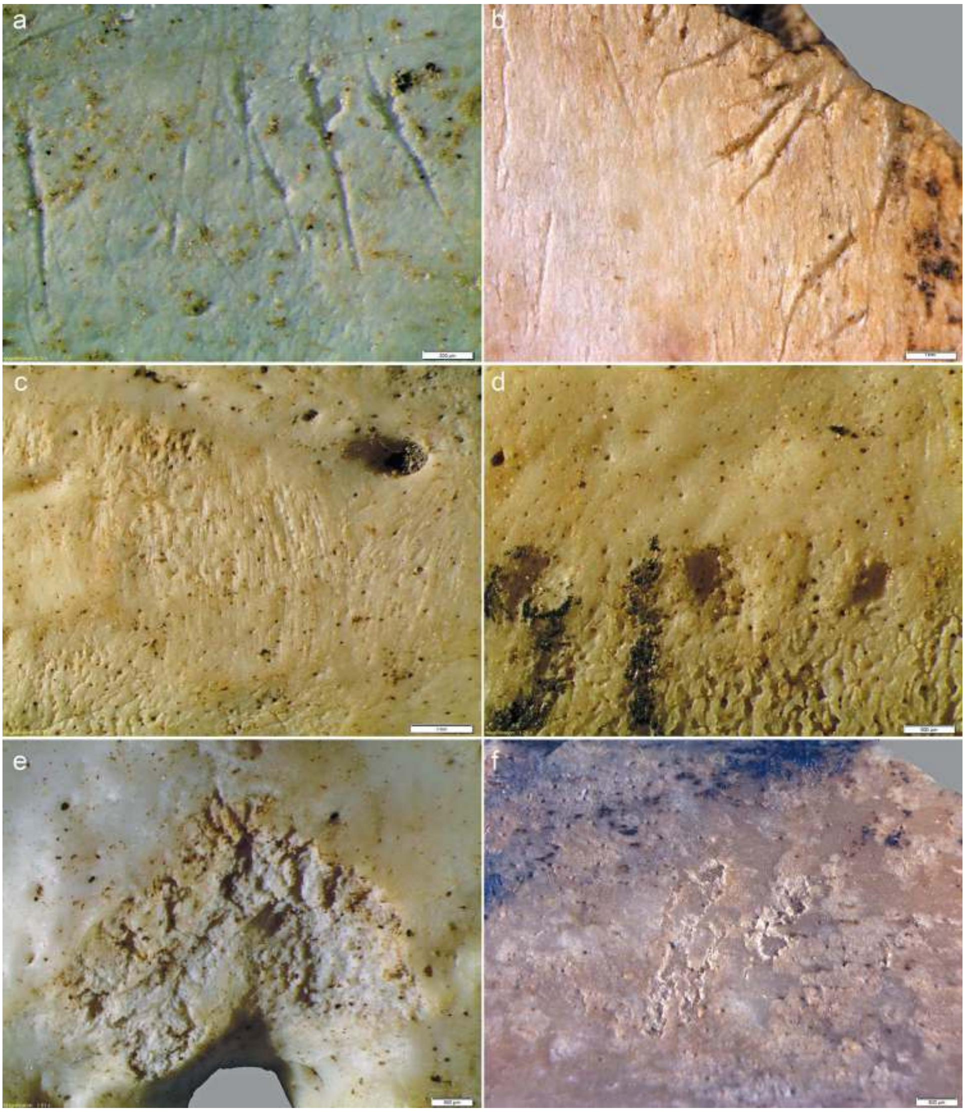

Figure 18.4 Trogid hide beetle (*Afromorgus squalidus*) damage to bone. (a) Shallow individual striations on fresh bone that are lens-shaped or have a head and a tail. In section they are V-shaped with a rounded base. (b) Broad and deep examples of individual striations near an edge. (c) Multiple fine parallel striations that cover a relatively large area on a dry weathered bird bone, and (d) pits with smooth bases on the same specimen. (e) A large rectangular pit with striations in the base is recorded on a second dry bird bone. (f) Pitting of a fresh bone surface. Scale in a = 200 µm, scales in b, c = 1 mm, scale in d = 400 µm, scales in e, f = 500 µm. (Reprinted from Dirks et al. 2015:19, Copyright [2015], with permission from eLife Sciences Publications Ltd. Creative Commons Attribution License, https://creativecommons.org/licenses/by/4.0/.)

Darkling Beetles (Tenebrionidae)

The Tenebrionidae form an extremely diverse taxonomic group with nearly 19,000 species described worldwide. These beetles are often a significant part of the entomological fauna of arid zones and island environments (Soldati 2007). Known colloquially as "darkling" or flour beetles, and in South Africa as "toktokkie", most species are sapro-detritiphagous,

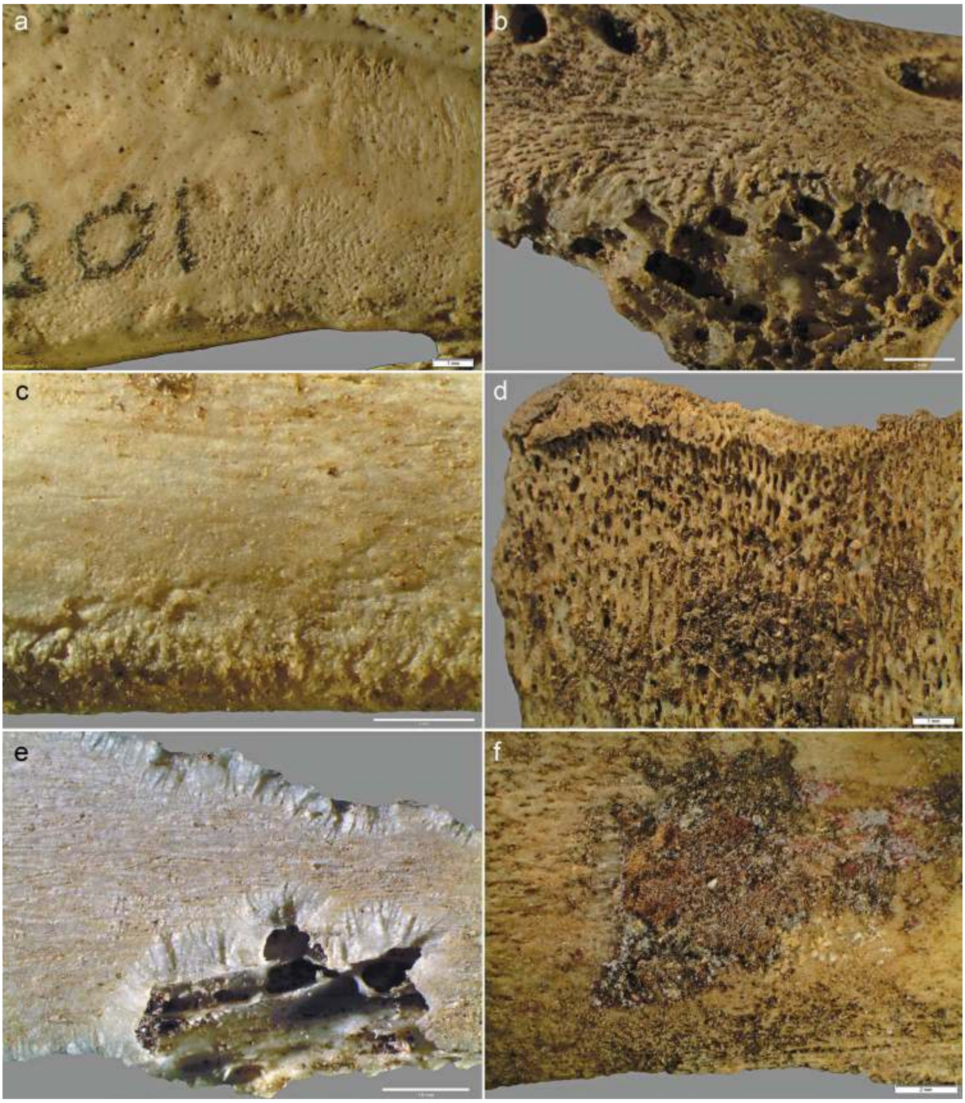

Figure 18.5 Trogid hide beetle (*Afromorgus squalidus*) damage to bone. (a) An etched surface appearance of a dry bird bone, (b) destruction of a fresh bovid distal phalanx, (c, d) surface removal on a fresh cow rib, (e) invasive edge gnawing on a dry medium size bovid rib, and (f) fungi (white dots) and microbial matter that has been harvested to the left on a fresh cow rib. Scales in a, c, d = 1 mm, scales in b, f = 2 mm, scale in e = 10 mm.

with larvae and adults feeding on fresh and decaying leaves and wood, dead insects and fungi. Tenebrionid bone modification is reported by Zacher (1927) and McFarlane (1971). In an experiment conducted by Holden et al. (2013), larval stages of both genera *Tenebrio* and *Eleodes* were provided with juvenile chicken bones, pork (*Sus scrofa*) ribs, juvenile pig metatarsi, and adult horse (*Equus caballus*), and sheep (*Ovis aries*) sesamoids. Damage was concentrated in more vascular bone, with bone favored over soft tissue consumption. The ribs and metatarsi received the least modification. The adult sheep and horse sesamoids were well ossified and remained untouched except for linear grooves and surface removal. Mandibular marks from both *Eleodes* and *Tenebrio* larvae were visible at

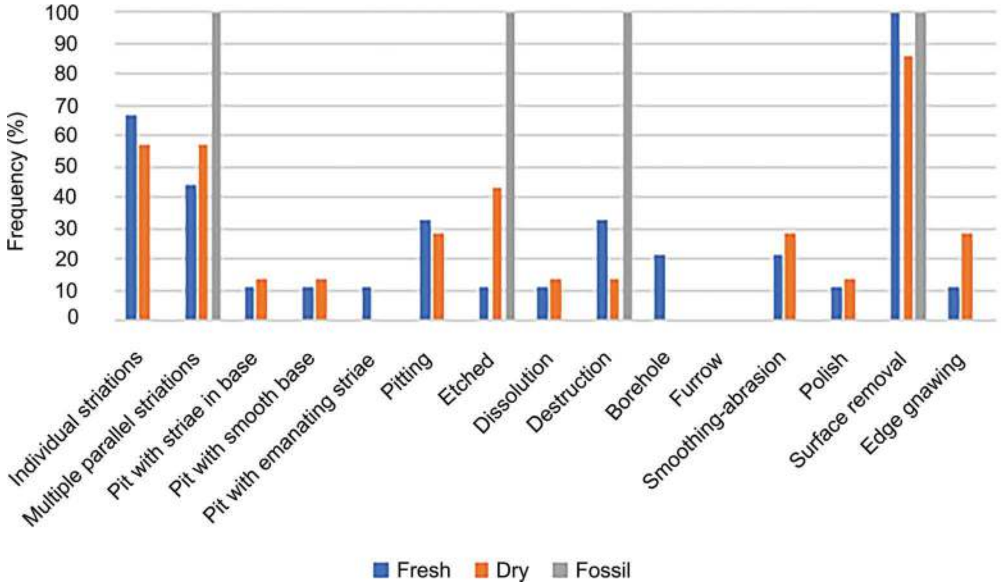

Figure 18.6 Type and frequency of damage created experimentally by Trogid hide beetles (*Afromorgus squalidus*) on bones in various states of preservation.

40× magnification on the bone surface as shallow and linear grooves, and also in shallow surficial mining. Tenebrionids created relatively smooth-surfaced traces, the result of consistent and extensive gradual bone removal.

We also conducted an experiment in which 11 bones were placed in a tank with 19 individuals of an unspecified South African tenebrionid species of the genus *Anomalipus* on inert palm peat from late January to May, austral summer into winter in 2012. After four months they were found to modify fresh and dry bone with equal frequency. Microscopic analysis revealed that they produced individual striations that are extremely broad, deep, and have a U-shaped base in cross section (Figure 18.7a). They also produced fine individual striations that occur approximately parallel to each other (Figure 18.7b). Two dry bone fragments recorded pits with a smooth base. A little over 60% of the specimens recorded an etched appearance, while pitting, destruction, furrowing, and polish were recorded on less than 20% of the specimens. All of the experimental bones showed removal of the surface in such a way that there was a step down from the surface to underlying cortical lamellae (Figure 18.7a, b). Even though eight of the types of traces made by tenebrionid beetles overlap with those made by trogid beetles, tenebrionids did not produce pits with striae in the base, pits with emanating striae, dissolution, boreholes or a smoothed and abraded surface appearance such as those on bones used in the trogid beetle experiment (Figure 18.8). The individual striations produced by tenebrionid mandibles (Figure 18.7a) are quite different from those made by trogid beetles (Figure 18.4a, b), in that they are more like gouges than striations, and are open-ended or vaguely lens-shaped, whereas trogid beetle striations are narrower and have heads and tails most of the time.

Museum or "Larder" Beetles (Dermestidae)

The family Dermestidae contains 66 genera and nearly 1700 species or subspecies worldwide (Háva 2018). To a large extent, the dermestids are scavengers that feed upon dry remains of

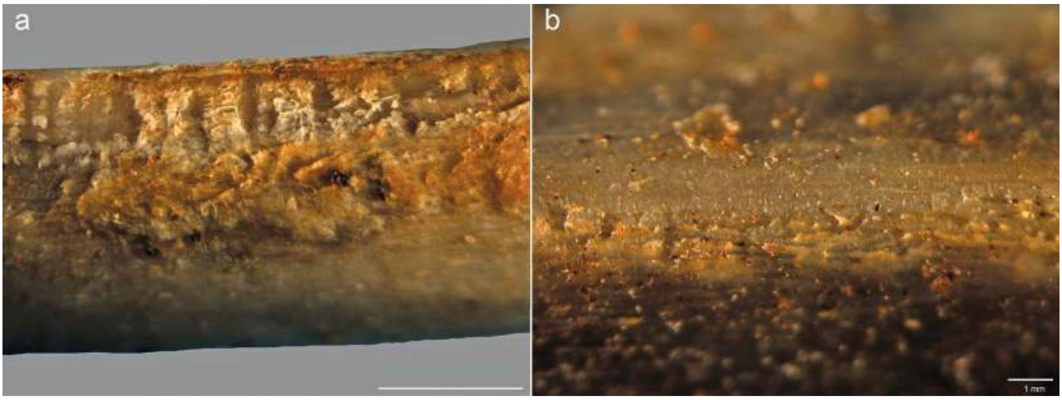

Figure 18.7 Tenebrionid beetle (*Anomalipus* sp.) damage. (a) Individual striations associated with surface removal on a fresh cow rib. The striations are deep and broad and have a U-shaped base in cross section. (b) Fine closely spaced individual striations on the same rib. Scale in a = 10 mm, scale in b = 1 mm.

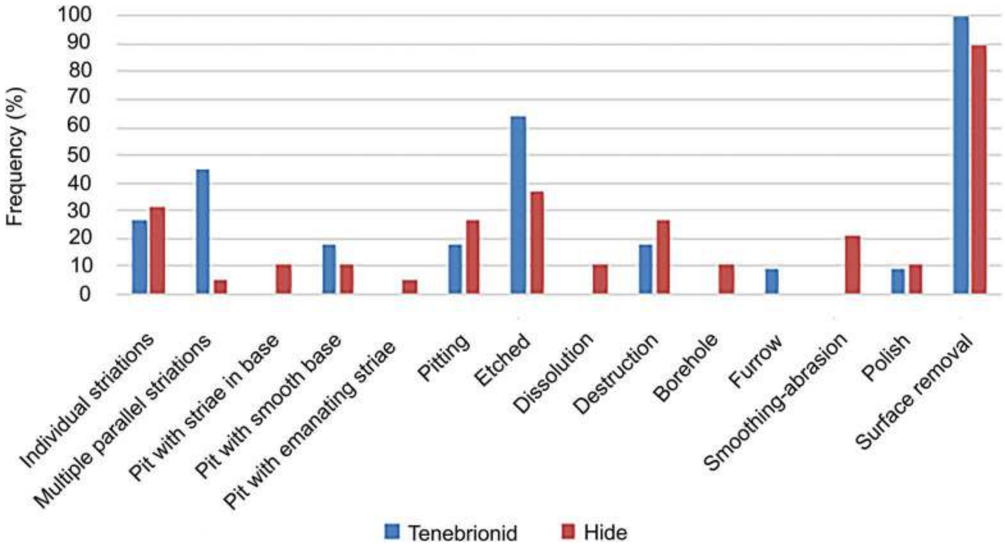

Figure 18.8 Type and frequency of damage observed on bones modified experimentally by tenebrionid (*Anomalipus* sp.) and hide beetles (*Afromorgus squalidus*).

animal origin (skins, hides, bones, fur, feathers, tendons, or dried meat) (Beal 1991; Hinton 1945; Peacock 1993). The genus *Dermestes* Linnaeus, which literally means "skinfeeders", includes nearly 80 worldwide species (Háva 2018). Several genera are primarily necrophagous (Beal 1991; Hinton 1945). The earliest report of bone modification by dermestids was by Gabel (1955), a finding later documented by Coe (1980) and Hefti et al. (1980). Schroeder et al. (2002) discussed dermestids as an accelerating factor in the decomposition of a human corpse. *Dermestes* damage includes destruction of small bones, borings through cancellous bone (Schroeder et al. 2002; Timm 1982), furrows on articular surfaces (Schroeder et al. 2002) and pit-like depressions resulting from feeding and boring for refuge and pupation (Zanetti et al. 2019). Modifications made by individuals of the genus *Dermestes* and their larvae are reported on bones from a museum collection in which they were used to clean the bones of soft tissue (Fernández-Jalvo and Andrews 2016; Fernández-Jalvo and Monfort 2008). No damage was visible with the naked eye, but microscopic analysis showed that the damage includes deep and straight incisions with and without ragged edges, holes with irregular edges that are sometimes sawed in outline, and chewing marks on the surfaces of bones. In a bone modification experiment conducted by Roberts et al. (2003) with *Dermestes*, the resulting damage included discrete oval-shaped borings through cortical bone to large irregular excavations in trabecular bone. Metaphyses of large limb elements were utilized more than any other type of bone. These authors noted that bone modification was most pronounced under conditions in which both food and substrate (for pupation/shelter) were restricted. Thus, the nature and extent of dermestid traces may serve as an indicator of a stressed habitat where food availability and nesting substrates are limited.

An experiment designed to record modifications made by *Dermestes maculatus* on fresh pig feet is described by Zanetti et al. (2014). Both adult and larval stages ate skin, flesh, tendon, cartilage, and bone. Beetles started to eat bones after approximately six months, when little soft tissue remained. Gnawing occurred on borders and surfaces of cancellous bones, and they made pits. Dermestid larvae damage to bone is well illustrated by Holden et al. (2013), who also conducted laboratory experiments with *D. maculatus* larvae that were fed immature chicken bones and pork ribs. Damage occurred on the softer and cancellous areas of bone for the purpose of making pupation chambers or mining lipids. Mandibular marks were not detected under 40× magnification. The damage categories include small and medium-size pits, circular with concave bases, 1.5–2.5 mm in diameter and 0.75–5.5 mm deep, especially on cancellous bone. Tunneling between 2.5–3.5 mm in diameter and over 5.5 mm deep was observed. Mining of bone sometimes created large adjacent pits, which together with edge grazing resulted in scalloped contours of bone removal. According to an experiment conducted with *D. maculatus* by Parkinson (2012), they created microscopic shallow pits with randomly oriented and often intersecting striations in the base, and produced star-shaped marks comprising individual striations radially arranged around a smooth-walled central cavity. The same feature is made by *Odontotermes badius* termites (Figure 18.2e). Parkinson's study showed that the distribution of modifications was mostly on epiphyses and at the diaphysis-epiphysis junctions, and that while *D. maculatus* preferentially modified dry bone, they also modified bone with fresh tissue attached, as reported by De Souza and Linhares (1997).

Carrion or "Burying" Beetles (Silphidae)

The Silphidae (carrion beetles) is a widely distributed family consisting of 15 genera and about 200 species worldwide (Dekeirsschieter et al. 2011). The family is divided into two subfamilies: the Silphinae, which have a worldwide distribution, and the Nicrophorinae, which occur primarily in the Northern Hemisphere. In North America 30 species in eight genera have been recognized (Peck 2000). The silphids are black or metallic blue-black carcass-breeding beetles. The name "burying beetle" is linked with the biology of these beetles, which bury small carcasses, close to which they lay their eggs, and on which both adults and their larvae feed. Following an experiment conducted with quail (*Coturnix japonica*) carcasses, *Nicrophorus americanus* were found to cause bone breakage, cracking, embedding, flaking, furrowing, pitting, polishing, and staining (Dirrigl and Perrotti 2014). Smooth, U-shaped shallow grooves are described as mimicking those produced by termites feeding on bone matrix, as reported by Kaiser (2000).

Hymenoptera

Ants (Formicidae)

The Formicidae family belongs to the order Hymenoptera, which also includes bees and wasps. Ants are eusocial insects and a conspicuous component of terrestrial biodiversity. With more than 12,000 described species (Bolton et al. 2006), ants figure among the most species-rich of all social insects. Their representatives occur virtually in all major terrestrial habitats, and their combined weight (biomass) corresponds to about 15%–25% of the total weight of terrestrial animals (Schultz 2000). Ants have colonized almost every landmass on Earth except Antarctica and a few remote islands. Ants occupy a wide range of ecological niches and exploit many different food resources as direct or indirect herbivores, predators, and scavengers. Most ant species are omnivorous generalists, but a few are specialist feeders. Go (2018) described ant damage to human remains contained in a rice sack that were used as a nesting substrate in a cemetery in the Philippines. The damage comprises holes with diameters ranging from less than a millimeter to 15 mm across. There is complete puncturing of bone to form perforations from the cortical bone into the medullary cavity. At low magnification, the holes have minutely scalloped edges, with some displaying radiating shallow striae. Go (2018) noted that some species produce formic acid as a form of defense and that the possibility of chemical action in tandem with physical mastication should be considered. The illustrated damage shows highly etched and thinned bone with destruction of cancellous bone.

We conducted a laboratory experiment with two types of ants: *Camponotus* sp. (carpenter ant) and *Linepithema humile* (large Argentine ant). The ants were collected from broken woodland near the Malapa site in South Africa. A few spadefuls from each colony were shoveled into two buckets, and nine experimental pieces of bone in different stages of preservation were added to each bucket. The experiment ran from March to June, in austral winter in 2013. Results showed that after three months both small and large ants made the same types of modifications to the bones (Figure 18.9). Both created individual striations and multiple parallel striations (Figure 18.10a, b). Both made pits with smooth bases and pitted the bone surface. Both caused an etched appearance (Figure 18.10c, d) and dissolution of bone, made furrows, smoothed and abraded bone, and removed the surfaces of bone in all specimens (Figure 18.10e, f). Destruction was the only feature in which the small and large ants differed, with large ants recording this damage and small ants not. Upon retrieval, all experimental bones had a sedimentary coating from ant activity.

Analysis of bones used in the two ant experiments revealed that the containers were contaminated with flies and mites. Puparia on a weathered bovid tooth (Figure 18.11a) were identified as those of "latrine flies" of the Family Fanniidae, many of which are highly synanthropic. Bones used in the small ant experiment were crawling with mites. They were observed feeding on the organic part of bone (Figure 18.11b–d) and appeared to be the cause of the etched appearance. According to acarologist Barry O'Connor (pers. comm.), virtually nothing is known about the fauna of astigmatid mites associated with carrion in Africa. Figure 18.11b shows mites feeding on the heavily etched surface of a rib that was fresh, with soft tissue attached. They appear to be species in the Family Histiostomatidae. There are a few genera in this family of filter-feeding mites that are carrion specialists: *Spinanoetus*, *Pelzneria*, and *Peripatetes*, all of which are phoretic (i.e., non-permanent

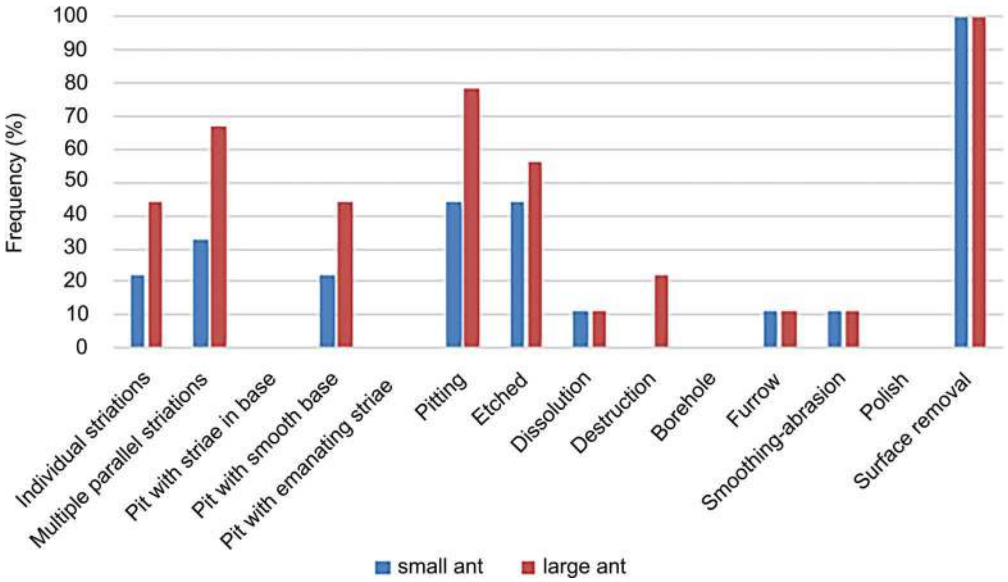

Figure 18.9 Type and frequency of bone modifications created experimentally by small (*Camponotus* sp.) and large (*Linepithema sinuate*) ants.

residing commensals) on silphid beetles. Some species of *Myianoetus*, all of which are phoretic on flies, are also known from carrion studies. It is also possible that the mites belong to the large genus *Histiostoma*, which may be found in many types of decaying organic matter. Figure 18.11c and d shows a species in the Family Acaridae, probably the genus *Sancassania* (*Caloglyphus* in older literature). These mites are generalists in decaying organic matter and are phoretic on many different insects, although they show a preference for Scarabaeidae beetles. Some *Sancassania* species can disperse through the soil in addition to using an insect host, so they may have found the experimental bone flakes in that manner. Juveniles are mostly represented in Figure 18.11c, and adults in Figure 18.11d. Contamination with flies and mites means that the ant experiment failed in ants not being the only possible taphonomic agents to have modified the bones. However, the presence of flies and mites reflects a more natural process of postmortem decay, one in which multiple agents affect the integrity of fresh bone.

Bees and Wasps (Halictidae and Sphecidae)

Excavations conducted in Italy at a cemetery dating to the Roman Empire led to the discovery of both ancient and modern bee and wasp damage on human remains (Pittoni 2009). The modifications described include round holes, irregular bone destruction, and irregular etching. These features were found mostly on the skulls and long bones, and to a lesser extent on the vertebrae, hands and feet. We characterize “irregular bone destruction” as approximately circular, extremely large flat-based pits with rounded margins. The damage to the bones was produced by three kinds of hymenopteran that build subterranean tunnels and nests, one of which belongs to the Family Sphecidae (sand wasps, mud daubers, and thread-waisted wasps), the other two to the Family Halictidae (sweat bees). In this case, nesting structures were constructed in bones. Of the 72 skeletons studied, 45 recorded holes in bones. Half of the holes had a diameter of between 6 and 7 mm. Nearly a

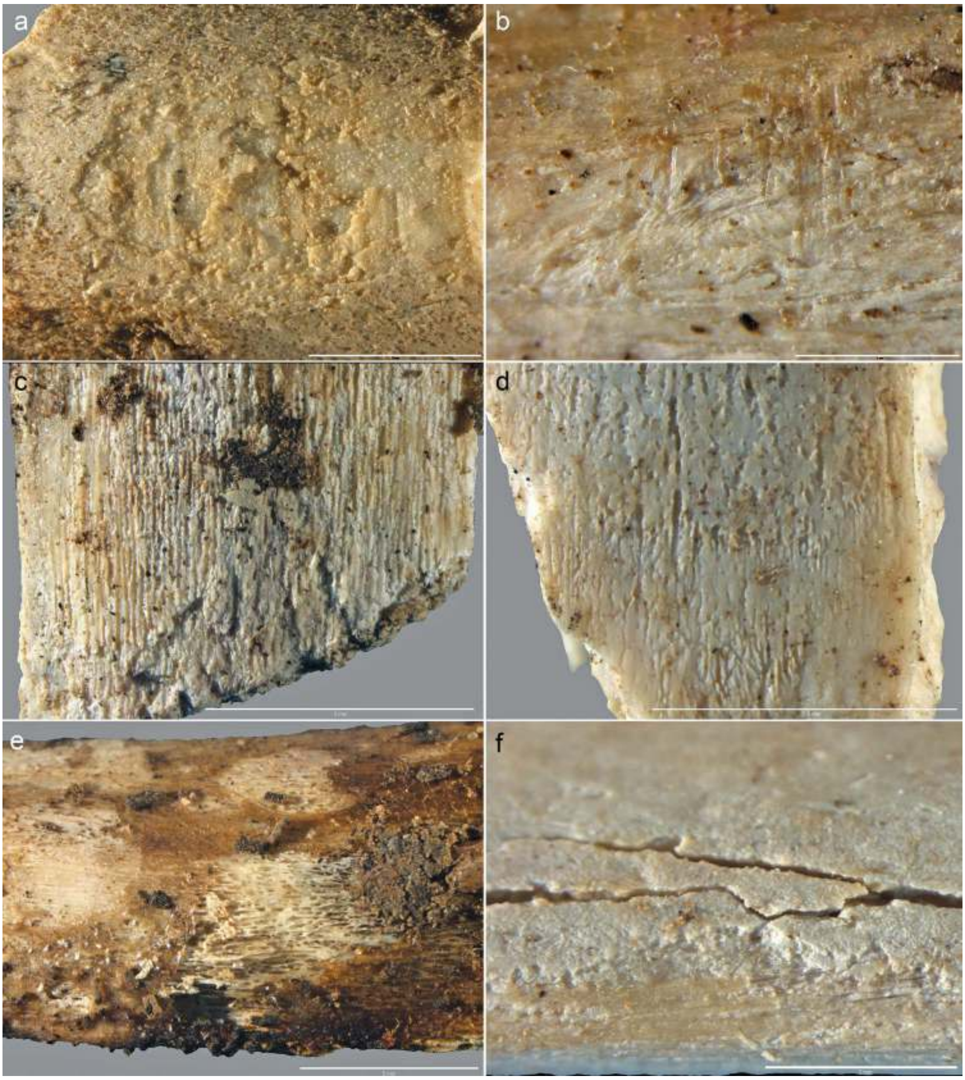

Figure 18.10 Damage to bone caused by large ants (*Linepithema sinuate*). Modification types include (a, b) multiple parallel striations, (c, d) an etched surface appearance and (e, f) surface removal. Scales in a, c, d, e = 5 mm, scale in b = 1 mm, scale in f = 2 mm.

third were 8–9 mm in diameter, and 8% were 10–20 mm across. Pittoni (2009) warned that taphonomists may misinterpret the origin of such holes, saying that single holes may be interpreted as weapon damage, while multiple holes could be mistaken for tumor damage (metastases) or trepanation.

Lepidoptera

Horn Moth (Tineidae)

The Tineidae (clothes-moth or horn-moth) comprises more than 2000 currently recognized species of small- to medium-sized moths (Robinson 2019). They differ from all other Lepidoptera in their unorthodox larval biology: most tineid larvae feed on keratinous

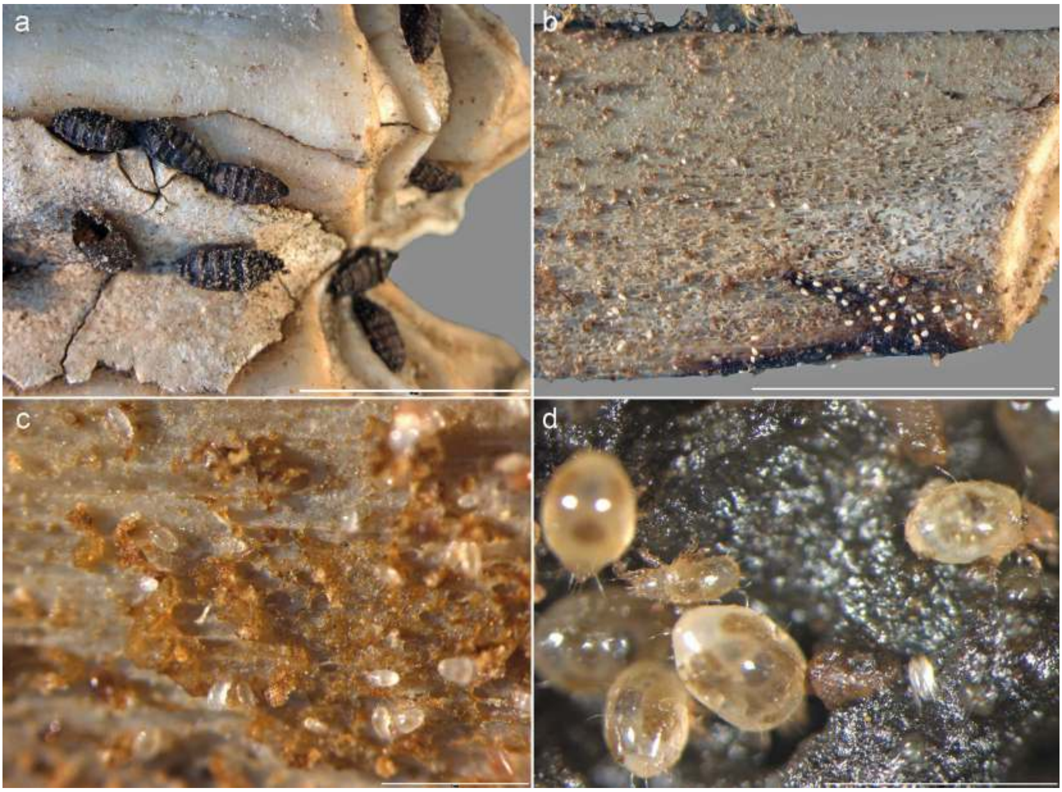

Figure 18.11 Contamination of the small ant (*Camponotus* sp.) experiment with latrine flies and mites. (a) Latrine fly puparia (Family Fanniidae) on a weathered bovid tooth. (b) Mites of the Family Histiostomatidae feeding on the surface of a rib that was fresh with tissue attached. Note the etching of the bone surface. (c) Juvenile mites of the Family Acaridae, and (d) adults of the same taxon. Scales in a, b = 10 mm, scales in c, d = 1 mm.

tissue, including skin, hair, nails, feathers, horn sheaths, and the surfaces of horn cores. They lay their eggs close to a keratin source for their emerging larvae to consume. The larvae make long grooves in horn cores or bone while feeding (Gifford-Gonzalez 2018). Modifications are visible with the naked eye and take the form of multiple relatively long and broad, smooth-based grooves at angles oblique or almost perpendicular to the main axis of the horn. Britt et al. (2008) explained that larvae gnaw through the horn sheath, creating elliptical holes through which they enter the space between the horn core and sheath to feed. *Tinea deperdella* and unspecified representatives of the genus *Ceratophaga* create shallow pits and ovoid, canoe-shaped excavations up to about 5 mm wide and 25 mm long on the surface of horn cores (Behrensmeyer 1978; Gentry 1987). Horn core damage is reported by Zacher (1927) and Hill and Behrensmeyer (1980), and is well illustrated by Behrensmeyer (1978) and Behrensmeyer et al. (1989).

Diptera (Various Carrion-Associated Families)

Fly Larvae

Diptera are among the first visitors to a fresh corpse, with females laying their eggs in natural orifices and wounds. In Cyclorrhaphae Diptera the larvae feed by sucking on hydrolyzed flesh, which is broken down by digestive enzymes that are regurgitated onto the tissue. Round, soft tissue damage on human cadavers caused by maggots is reported by Pollak and Reiter (1988), who described them as similar in appearance to gunshot wounds. They noted that the larvae of some types of flies bundle together to form feeding communities known as maggot masses (Heaton et al. 2014), and that the enzymes from the salivary glands of the maggots may in some instances lead to perforation of bone lamellae, for example in the region of the orbital roof. Gładykowska-Rzeczycka and Parafiniuk (2001) suggested that certain atypical lesion areas on the internal surface of the cranial vault and the cervical vertebrae of a juvenile human (Poland, 8th century) appeared to result from the corrosive action of digestive juices from Diptera larvae.

We conducted two bone modification experiments with flies and their larvae for one month at the end of austral winter (July-August) in 2011. In the first experiment, 12 pieces of bone (represented by fresh and dry medium-sized bovid bone fragments, and fresh and dry bird femora) were placed in an inverted bucket-type flytrap, which was hung in a tree in Johannesburg to attract garden flies. Using hanging traps baited with liver and fish, Parry et al. (2016) collected 59,511 adult Diptera, identified to 35 species in eight different families from in and around the City of Tswane, adjacent to Johannesburg. The most abundant carrion-associated Diptera taxa include *Chrysomya megacephala*, *C. chloropyga*, *C. putoria*, *Muscina stabulans*, *Atherigona* sp., and *Ophyra anthrax*, and it is likely that the same taxa are represented in our study.

We do not know how many flies were trapped, but the bucket was swarming with them, and when the larvae emerged, they formed a thick bed on the bottom of the container. The other experiment was conducted with latrine flies of the genus *Fannia* in the laboratory using the same selection of bones. Garden fly maggots were found to modify fresh and dry bone equally and favored cancellous over cortical bone. The fly larvae produced a few very fine, randomly oriented individual striations (Figure 18.12a) and surface gnawing that sometimes resulted in multiple parallel striations (Figure 18.12b). They produced pits with smooth bases and pitted the bone (Figure 18.12c). Unlike the pitting caused by termite and hide beetle mandibles, which create shallow angular impressions, the larval mouthparts create clusters of tiny, approximately round cup-shaped pits with irregular edges. Flies and their larvae removed the periosteum, leaving an etched surface appearance (Figure 18.12d). They caused destruction of cancellous (Figure 18.12e) and cortical bone (Figure 18.12f). The larvae removed large areas of surface bone from a fresh rib that originally had soft tissue attached (Figure 18.13a) and a dry bovid rib (Figure 18.13b), periosteum from another fresh rib (Figure 18.13c), and the outer cortical lamellae of a dry bird bone (Figure 18.13d). Only one specimen showed no modifications, and it was a dry medium-size mammal piece of cortical bone. The types of damage caused by garden flies and their larvae and the frequency with which they occurred are shown in Figure 18.14. No data were collected on the bones modified by latrine flies and their larvae, but photographs of the specimens show that they produced the same type of damage as garden flies. Figure 18.13e shows how latrine fly larvae removed the bone surface and created a pile of bone fraction. The lower half of the bone flake has an etched appearance due to the exposure of underling bone. Figure 18.13f shows how larvae removed the outer layers of bone. For such a tiny fly, the damage created by its larvae is remarkable.

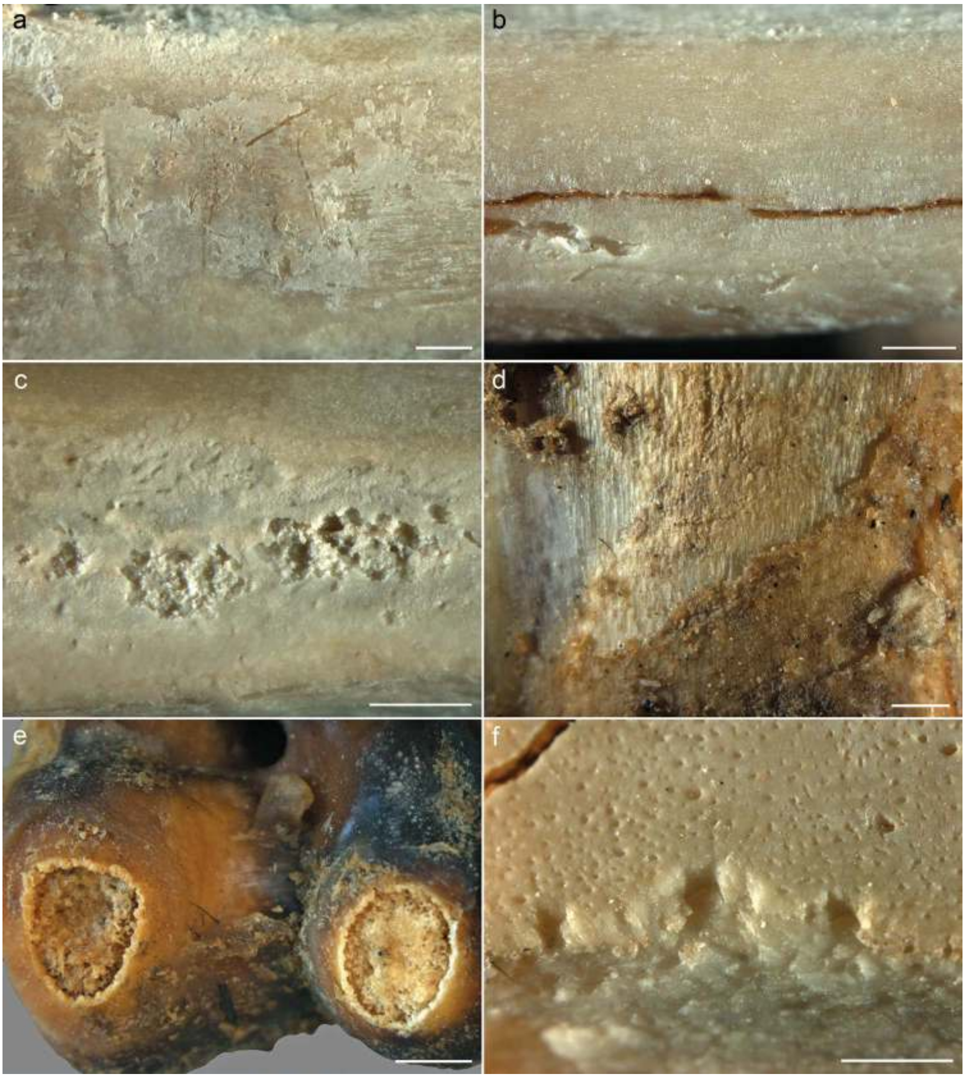

Figure 18.12 Fly larvae damage to bones. (a) Very fine individual striations on the surface of a heavily gnawed dry rib, (b) fine multiple parallel striations, and (c) pitting on the same bone. The larvae make clusters of tiny round cup-shaped pits with irregular edges. (d) Etched surface appearance of a fresh cow rib. (e) Destruction of cancellous fresh bird bone and (f) compact fresh sheep bone. Scales = 1 mm.

Orthoptera

King Cricket (Anostostomatidae)

Orthoptera (grasshoppers, locusts, and crickets) is a very large order of insects including 40 families and nearly 24,000 species (Ingrisch 2011). Orthopteran insects have a worldwide distribution and can generally be recognized by their ability to produce sound. Anostostomatidae is a family widely distributed in the southern hemisphere (South America, South Africa, Australia, and New Zealand). These insects usually feed on a combination of insects, fungi, dead animals, and fruit. Cricket modification of bone is

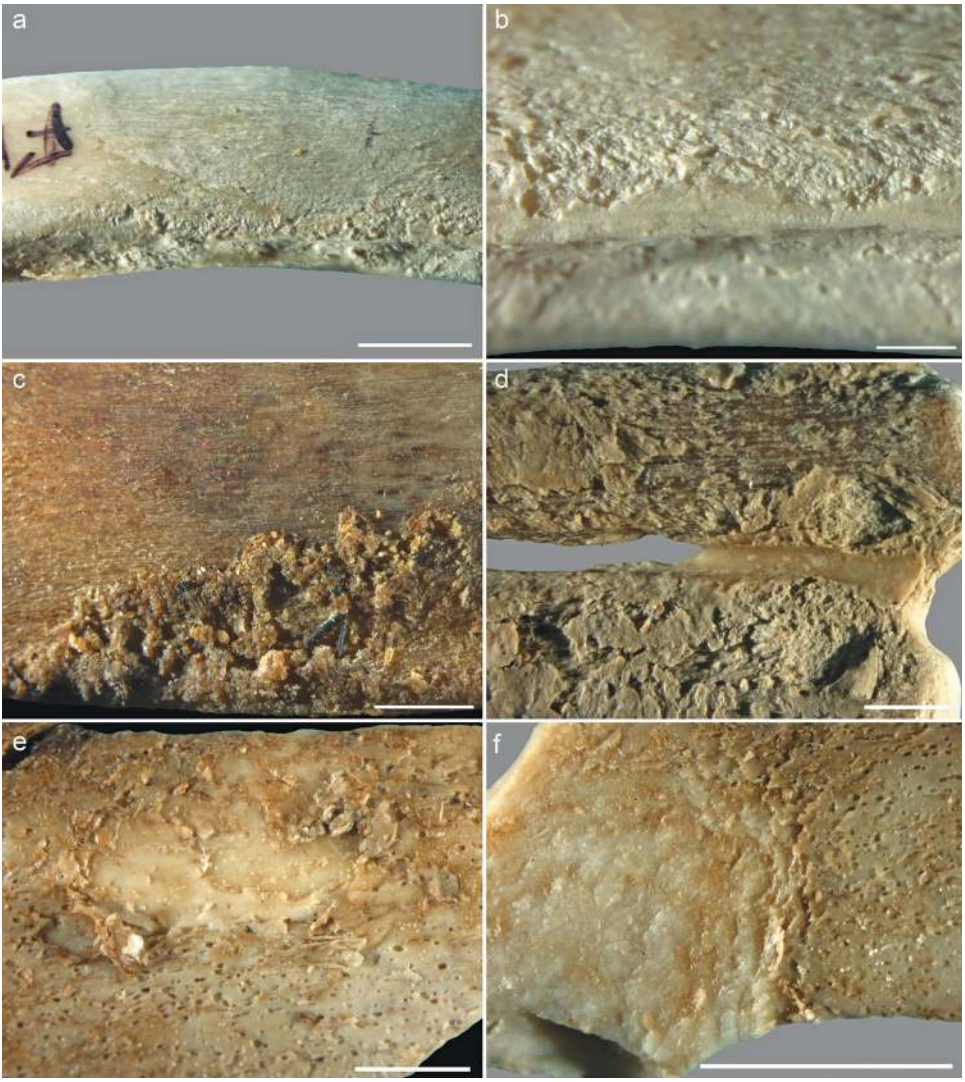

Figure 18.13 Fly larvae damage to bone. Surface removal by garden fly larvae on (a) a fresh cow rib, originally with tissue attached, (b) a dry bovid rib, (c) a second fresh rib and (d) dry bird bone. (e, f) Surface removal by latrine fly larvae from a fresh long bone flake. Scale in a, f = 10 mm, scales in b-d = 1 mm, scale in e = 2 mm.

represented by *Libanasidus vittatus*, also known as the African king cricket and Parktown prawn. King crickets are not true crickets; they belong to the Family Anostostomatidae, whereas true crickets are in the Gryllidae. *Libanasidus vittatus* have large, tusk-like mandibles, are omnivorous, and have been observed feeding on slugs, snails, invertebrates, vegetable matter, carrion, pet food, and dry oatmeal.

We conducted a bone modification experiment with two king crickets and 17 bone specimens on inert palm peat in austral summer, from January to May in 2011. Within days, one of the crickets pulled a fresh chicken femur with tissue attached into a subterranean tunnel. After three and a half months, the crickets had modified fresh and dry bone equally, but fresh bones showed more etching and destruction. The crickets produced

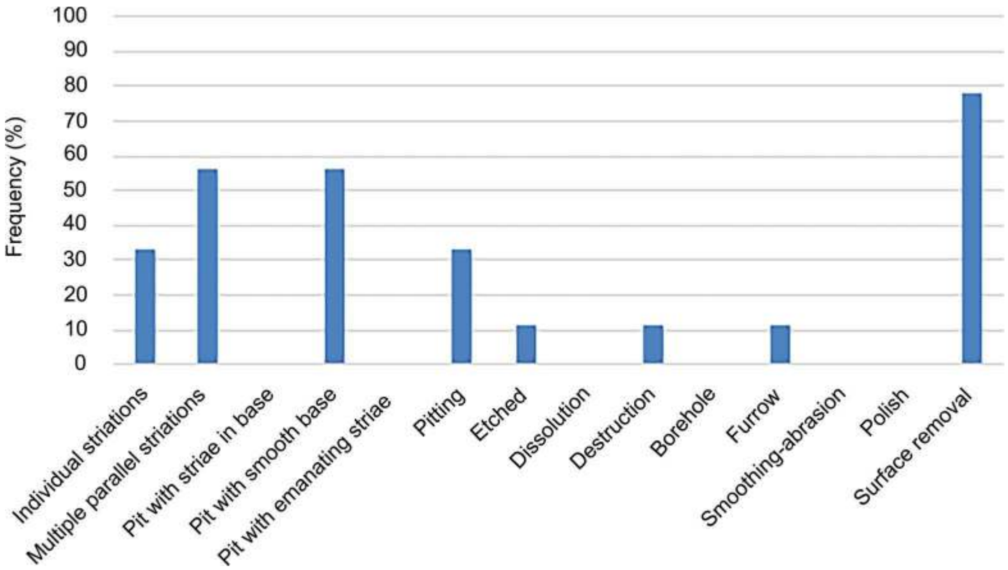

Figure 18.14 Type and frequency of damage caused by garden fly larvae.

multiple parallel striations on edges and ridges (Figure 18.15a) and groups of fine multiple parallel striations on surfaces (Figure 18.15b). They made one pit with emanating striations and pitted the bone surface. Etching was recorded on all of the fresh specimens (Figure 18.15c), and one showed dissolution. Crickets destroyed bone (Figure 18.15d), made a borehole, and polished one piece. Almost all of the specimens showed traces of surface removal. Microscopic analysis of the bones revealed the presence of a desiccated latrine fly larva (Family Fanniidae), Acarid mites (Figure 18.15e) that were probably introduced by the crickets, and unidentified microbes (Figure 18.15f) that are likely responsible for much of the etched appearance of the fresh bones. Figure 18.16 shows the type and frequency of damage caused by king crickets. The set of features that characterize cricket damage, in particular fine multiple parallel striations, is similar to that made by hide and Tenebrionid beetles (Figures 18.7b and 18.8) and woodlice (Figures 18.20a and 8.21).

Diplopoda

Spirostreptida

Millipedes (Spirostreptidae)

Spirostreptida are long, cylindrical millipedes arranged in three families (Harpagophoridae, Odontopygidae, and Spirostreptidae), including approximately 1000 species worldwide. Most millipedes are detritivores (eating decomposing plant and animal parts including feces), but some eat fungi, while others suck plant fluids, and a small number are predatory. A few species are carnivorous, and a few others eat moist living plant material (Shear 2011). *Archispirostreptus gigas*, known as the giant African millipede and "shongololo" in South Africa, is the largest extant species of millipede. A laboratory experiment was conducted with 10 millipedes (*A. gigas*) on inert palm peat in austral summer, from January to May in 2012.

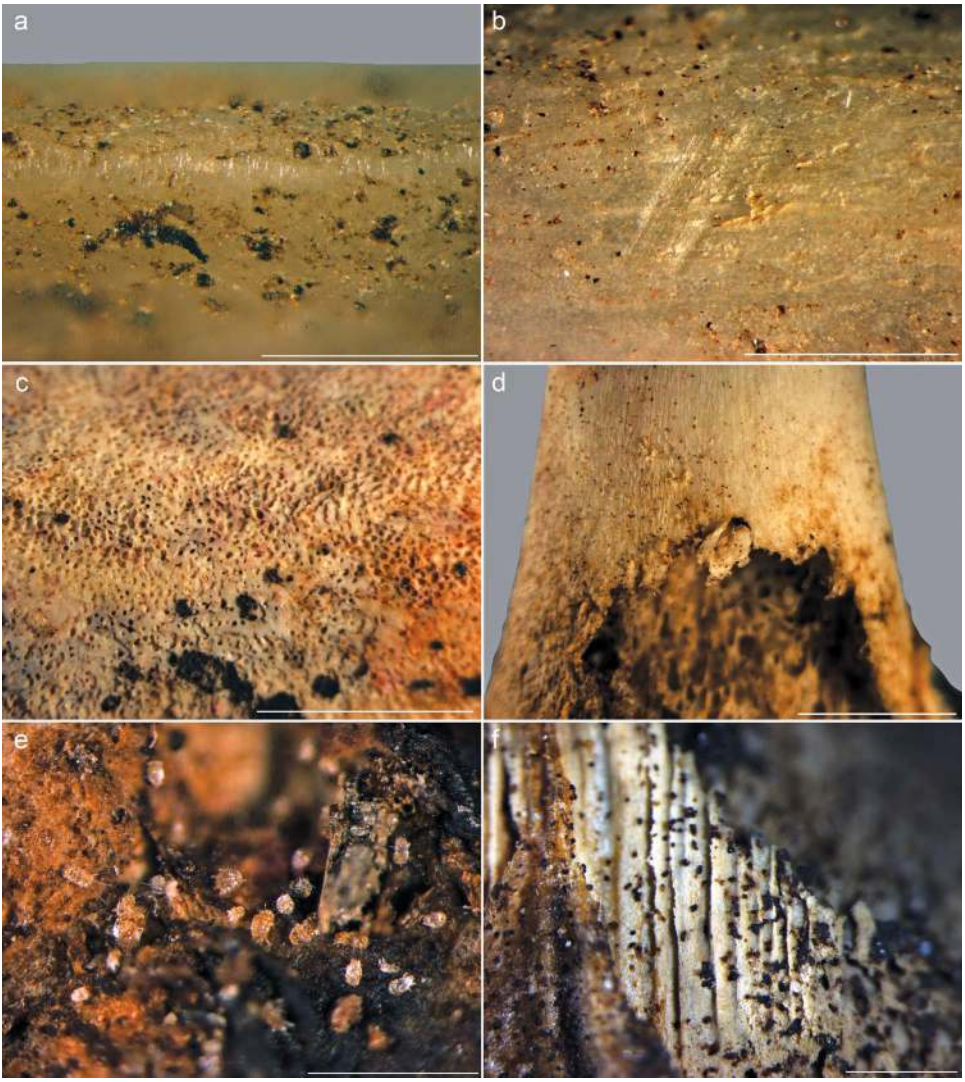

Figure 18.15 King cricket (*Libanasidus vittatus*) damage. (a) Fine, closely spaced individual striations, and (b) multiple parallel striations on a dry bovid rib. (c) Etching on a fresh sheep (*Ovis aries*) long bone flake, and (d) destruction of a fresh bird bone. (e) Acaridae mites and (f) unidentified microbes on a fresh bird long bone. Scales in a, b, c, e, f = 2 mm, scale in d = 10 mm.

Eight pieces of bone that were fresh with tissue attached or dry and weathered, were placed in the tank with the millipedes. After four months, microscopic analysis showed that they modified fresh and dry bone with equal frequency. At low magnification, a few individual striations were observed. The millipedes created a pit with a smooth base and pitted the bone surface (Figure 18.17a). More than half of the bones showed etching of the surfaces, some smoothing and abrasion and polish. Three-quarters of the bone specimens exhibited surface removal (Figure 18.17b, c) and a few showed destruction in the removal of large areas of bone (Figure 18.17d).

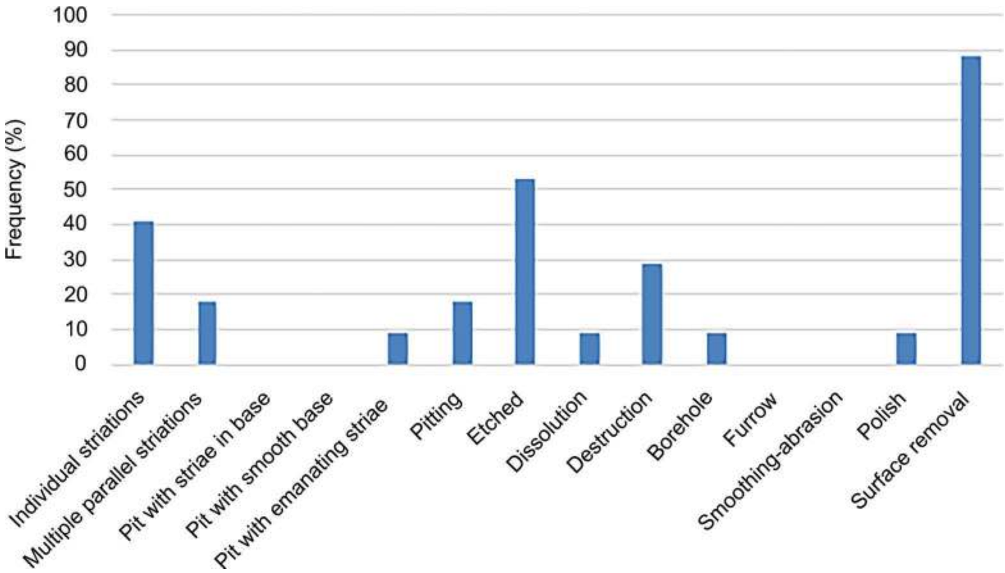

Figure 18.16 Type and frequency of damage caused by king crickets (*Libanasidus vittatus*).

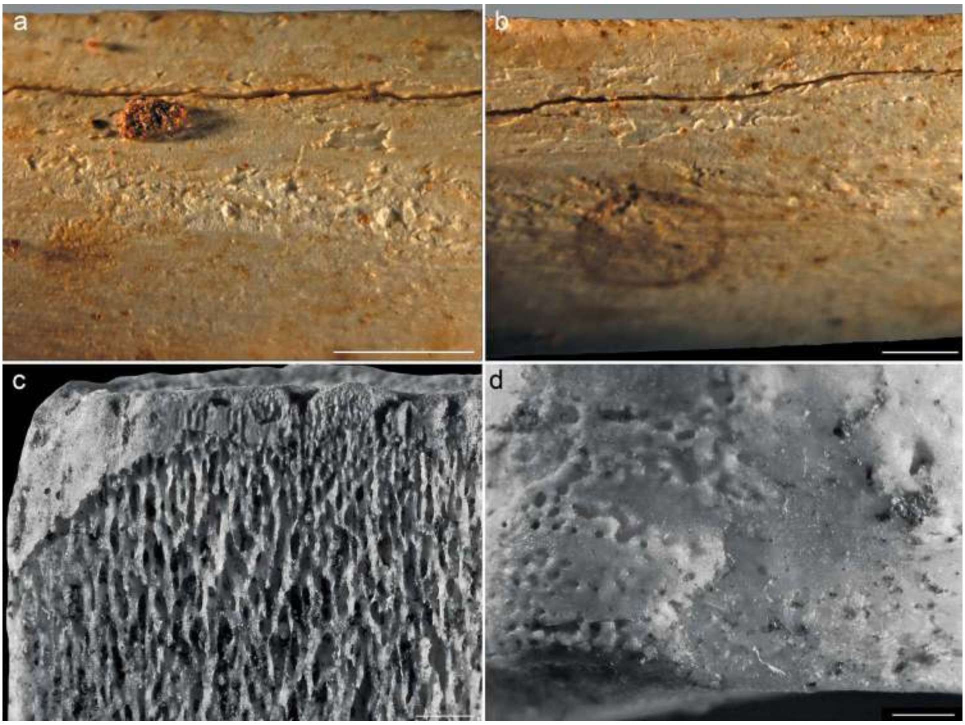

Figure 18.17 Millipede (*Archispirostreptus gigas*) damage to bone. (a) Pitting on a dry rib, surface removal on (b) a dry bovid rib and (c) fresh cow rib, and (d) destruction of a fresh sheep (*Ovis aries*) phalanx. Scales in a, b = 10 mm, scales in c, d = 1 mm.

Sphaerotheriida

Pill Millipedes (Sphaerotheriidae)

Giant pill millipedes of the order Sphaerotheriida are currently known from more than 300 species in 34 genera distributed in South Africa, Madagascar, India, Sri Lanka, southeast Asia, Australia, and New Zealand (Wesener 2014; Wesener et al. 2010). Large-bodied pill millipedes are named for their ability to roll-up into a spherical ball as a defense mechanism when disturbed. Pill millipedes are detritivores, feeding on dead organic matter such as leaves and wood on the forest floor. A laboratory experiment was conducted with two pill millipedes (*Sphaerotherium* cf. *modestum*) at the end of austral summer, from March to May in 2012. Nine pieces of bone in various stages of preservation were placed in the tank. After two months the pill millipedes had modified fresh and dry bones equally and had produced 12 types of damage. They made individual striations (Figure 18.18a), often parallel to each other, and multiple parallel striations along edges (Figure 18.18b) and on surfaces of bone (Figure 18.18a). More than half of the bone specimens recorded pits (Figure 18.18c), either with smooth bases, or with tiny cups in the base of them (Figure 18.18d) caused by the tips of the pill millipede mandibles. Pits with cupped bases appear to be a feature specific to pill millipedes. One pit had striations in the base. More than half of the bones showed an etched appearance resulting from surface removal (Figure 18.18e), and some showed dissolution. Surface removal was recorded on all specimens used in the experiment and manifested as areas of extreme smoothing, sometimes polished, and comprising very fine multiple parallel striations (Figure 18.18a, f). When we compare pill millipede and millipede damage, we see that pill millipedes create more types of damage (Figure 18.19) and that there is overlap between the two in some categories, which include individual striations, pits with a smooth base, pitting, etching, destruction, polish, and surface removal. Some of the modification features made by millipedes and pill millipedes overlap in type and frequency with those made by ants, termites, flies, and king crickets, so distinguishing between these agents is difficult and contextual information is essential to propose a reliable diagnosis.

Malacostraca

Isopoda

Woodlice (Porcellionidae)

Woodlice inhabit moist environments, taking shelter in dark damp places such as forest litter. They feed on fungi and detritus. We conducted a bone modification experiment with 30 woodlice of the genus *Porcellio* in a tank with inert palm peat from late January to June, which was austral summer to mid-winter in 2012. Nine bone specimens in a fresh and dry state were placed in a tank with the woodlice and retrieved for study after five months. Results showed that the woodlice modified fresh and dry bone with equal frequency. The mandibles produced extremely fine individual striations, but they never occurred in isolation—they occurred as sets of multiple, parallel, extremely fine striations on bone surfaces (Figure 18.20a) and edges, which were sometimes scalloped by edge gnawing (Figure 18.20b). Microscopic multiple parallel striations all over the bones characterize woodlice gnawing. They made one smooth-based pit and a borehole. They

Figure 18.18 Pill millipede (*Sphaerotherium* cf. *modestum*) damage to a dry bovid rib. (a) Individual striations that are closely spaced and approximately parallel to each other. (b) Multiple parallel striations along the edge, and (c) pits. (d) Pits with cups in the base is a feature specific to pill millipedes. (e) Etched surface caused by removal of the outer cortical lamellae, and (f) localized area of surface removal. Scales in a–d, f = 1 mm, scale in e = 10 mm.

polished a dry bird long bone and caused destruction on nearly half of the specimens (Figure 18.21). More than half of the bones had an etched appearance (Figure 18.20c), while one recorded dissolution. Microscopic analysis revealed that fungus was growing on fresh specimens (Figure 18.20d), but to what extent it modified the bones we do not know. Fungal hyphae penetrate the subsurface of bone and secrete enzymes and so are likely responsible for some of the etching observed. As with termites, the woodlice probably harvested the fungus.

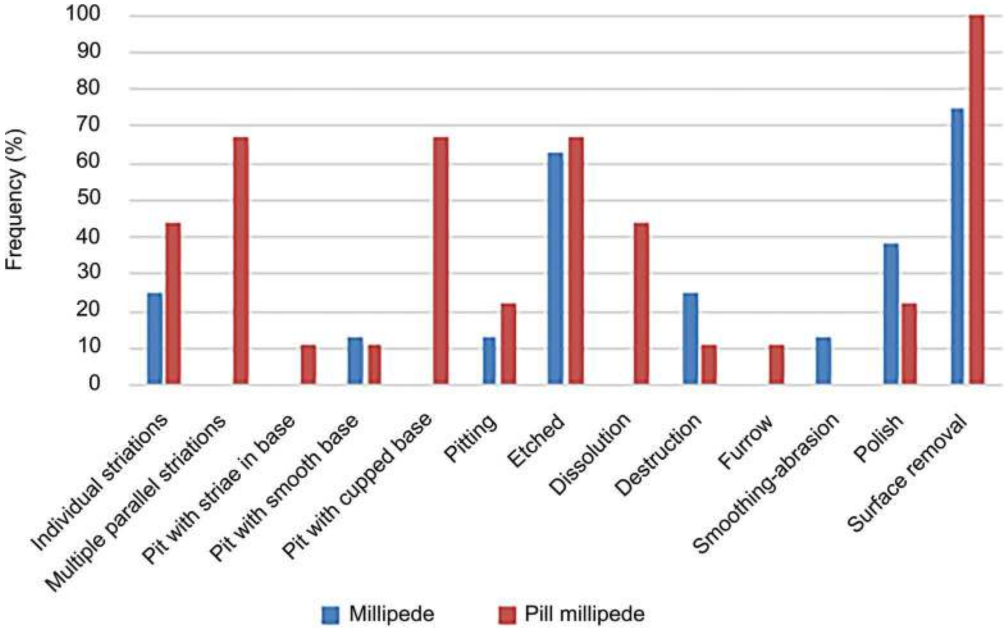

Figure 18.19 Type and frequency of modifications made by millipedes (*Archispirostreptus gigas*) and pill millipedes (*Sphaerotherium* cf. *modestum*).

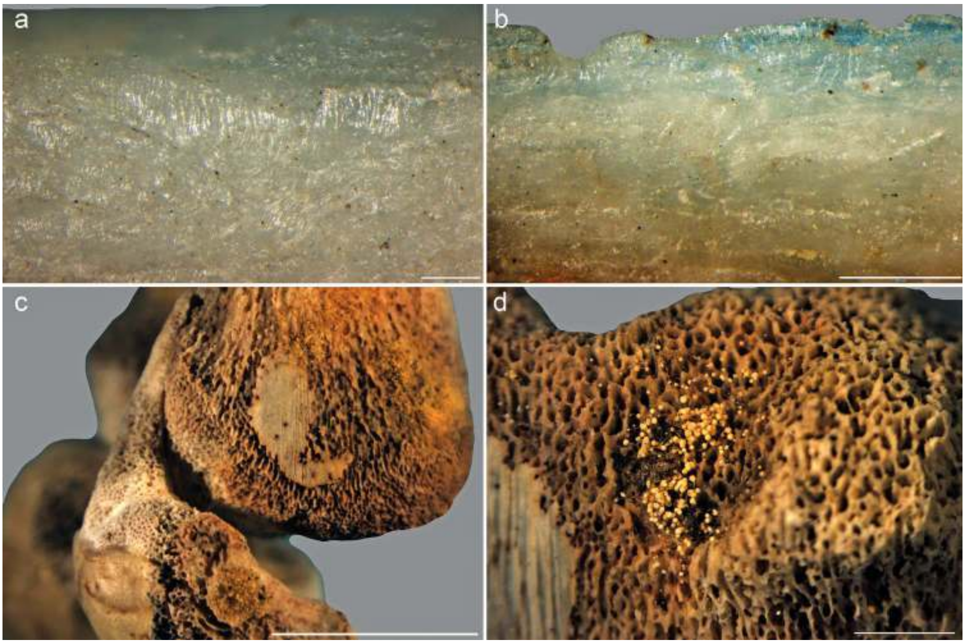

Figure 18.20 Woodlice (*Porcellio* sp.) damage. (a) Multiple parallel striations on the surface of a fresh cow rib and (b) along an edge. The edge is scalloped due to gnawing. (c) An etched surface appearance on a fresh bird distal femur and (d) fungus growing on the same specimen. Scale in a = 200 µm, b = 500 µm, c = 10 mm, d = 1 mm.

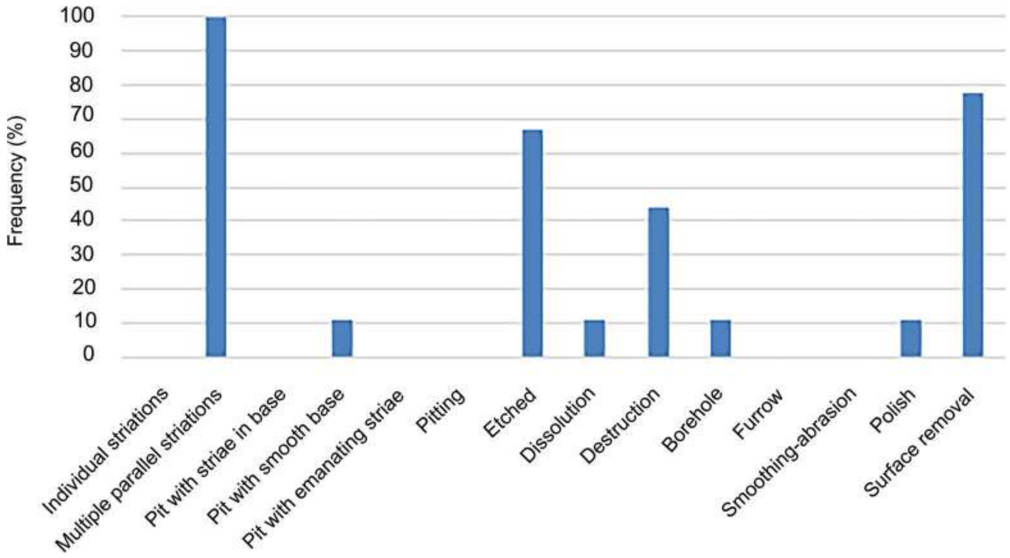

Figure 18.21 Type and frequency of damage caused by woodlice (*Porcellio* sp.).

Gastropoda

Terrestrial snails prefer cool, damp environments. They are herbivorous, utilizing a wide range of food sources, including fungi, algae, lichens, fresh or decaying plant leaves, flowers, fruits, seeds, and roots. Strictly plant-eating snails may occasionally scavenge on carrion, crushed members of their own species, and their eggs. They are also arboreal phylloplane grazers, scraping off the largely invisible film of microbial life on plant surfaces (Herbert and Kilburn 2004). The mouth has a tongue-like structure called a radula that is composed of hundreds of fine chitinous teeth (Figure 18.22a, b). The radula rasps/grates the surface of food and may, in combination with the jaw, cut food into small fragments to swallow. Snails require calcium carbonate for shell construction and obtain this from soil, sea spray, or by rasping soft calcareous rocks and the empty shells of dead snails. The sole of the foot produces an acidic secretion that can dissolve calcareous material to such an extent that they create holes in other snail shells and dissolve hollows in limestone rocks, of a size in which they can shelter (Herbert and Kilburn 2004).

Stylommatophora

Giant African land snail (Achatinidae)

Achatina sp.

A bone modification experiment was conducted with three snails of the genus *Achatina* in a tank with inert palm peat from late January to June, austral summer and winter in 2012. Thirteen bone fragments (fresh with tissue attached and dry) and a dry bovid tooth were placed in the tank. Results show that after four months the *Achatina* sp. modified fresh and dry bone with equal frequency. More than half of the specimens had individual striations, and over 90% recorded multiple parallel striations (Figure 18.22c–f). The striations occurred on all surface areas and edges. Unlike the multiple parallel striations made

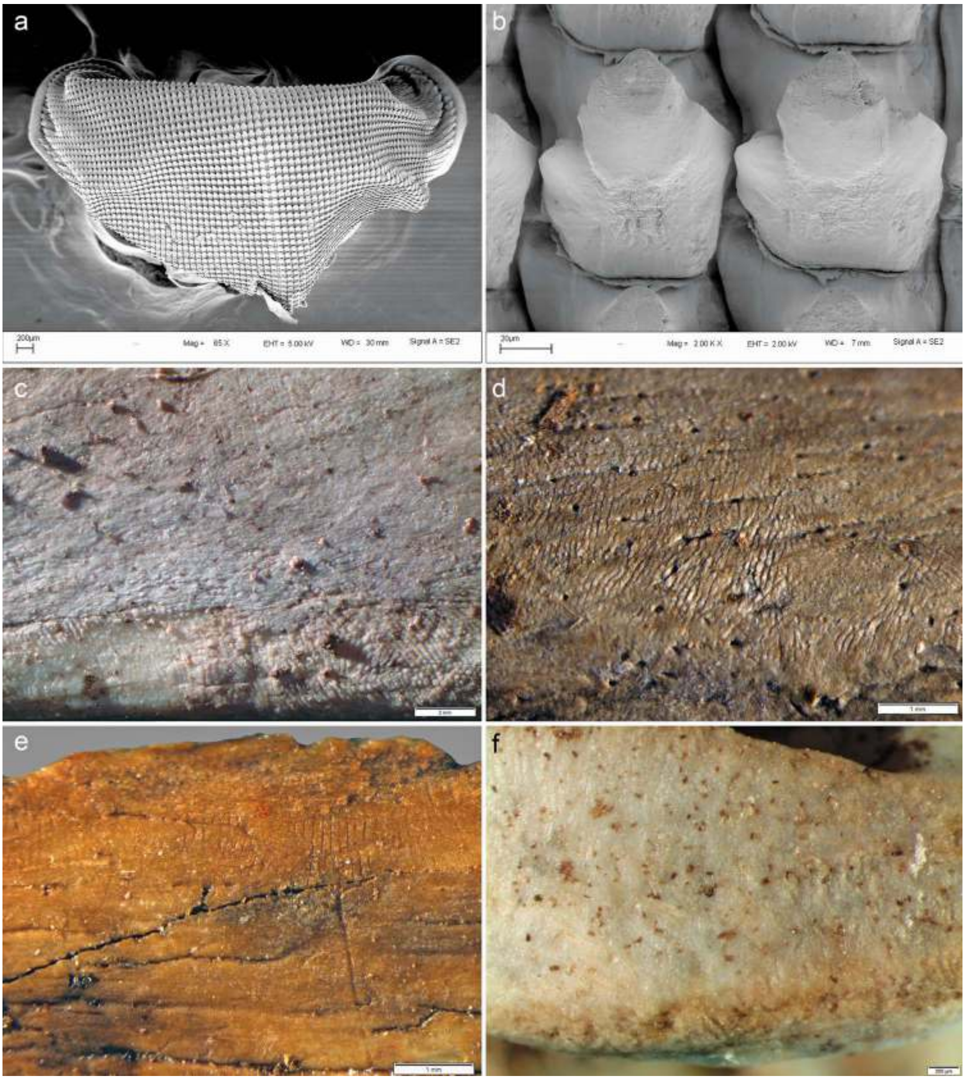

Figure 18.22 *Achatina* sp. radula and the damage it made to bones used in an experiment. (a) Scanning electron micrograph of the radula at low magnification and (b) close up showing the chitinous teeth. (c) Evenly spaced multiple parallel striations on a dry bovid rib, (d) on the surface and (e) along the edge of the same bone. (f) Multiple parallel striations on the distal femur of a fresh bird bone. Scraping of the radula in the same area created overlap that resulted in damage reminiscent of small rodent gnawing. Scales in a = 200 µm, b = 20 µm, c = 2 mm, d, e = 1 mm, f = 200 µm.

by other invertebrates, the striations made by the snail are evenly spaced and regular in their shape and depth (Figure 18.22e). In one instance, the multiple parallel striations on a bird distal femur overlapped and were less distinct and mimicked small rodent (Chapter 9) edge gnawing (Figure 18.22f). One specimen had a pit with striations in the base, and 77% of them had pits with smooth bases, some quite round (Figure 18.23a) and others oblong due to round ones being etched close to each other (Figure 18.23b). Pitting was recorded on 46% of specimens, etching (Figure 18.23c) on 70%, and dissolution on 23%. Destruction of enamel and dentine was observed on a dry bovid tooth (Figure 18.23d). Smoothing and

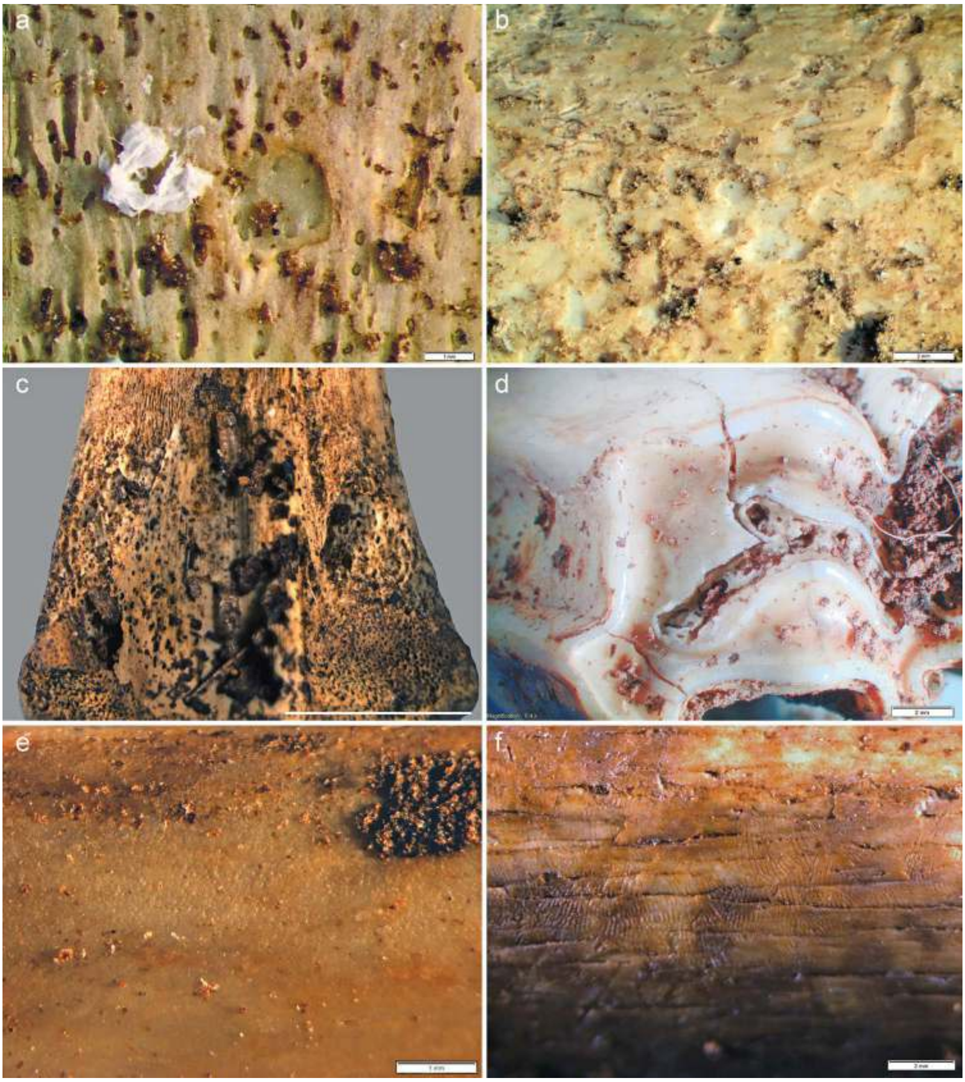

Figure 18.23 Damage made by *Achatina* sp. snails to bones used in an experiment. (a) Pit with a smooth base on a fresh bird bone, and (b) round and oblong pits on a fresh cow rib. (c) An etched appearance on a fresh bird bone. (d) Destruction of enamel and dentine on a dry bovid tooth. (e) Smoothing and abrasion on a dry bovid rib, and (f) surface removal on a dry bovid long bone fragment. Note the step down from the outer cortical lamellae along the top of the image. Scales in a, e = 1 mm, scales in b, d, f = 2 mm, scale in c = 10 mm.

abrasion occurred on 30% of the specimens (Figure 18.23e), as did polish, while surface removal occurred on nearly all specimens (Figure 18.23f).

Microscopic analysis of the experimental bones revealed the presence of latrine fly puparia (Family Fanniidae) among the microbial matter covering the surfaces (Figure 18.23c). There is overlap in the types of damage caused by fly larvae and snails, in that they both produce individual striations, multiple parallel striations, pits with smooth bases, pitting, etching, destruction, and surface removal. The extremely regular and evenly spaced multiple parallel striations made by a snail radula and the relatively large smooth-based pits are distinguishing features of snail activity, but to what extent fly larvae pitted, etched,

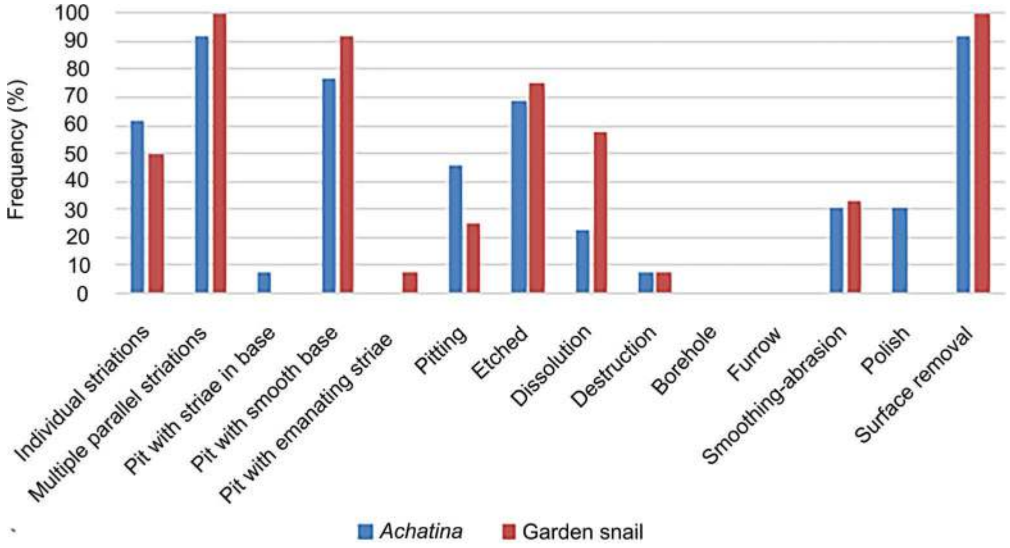

Figure 18.24 Type and frequency of damage made by snails. *Achatina* sp. and garden (*Helix aspersa*) snails produce a similar set of modification features, with much the same frequency.

and removed the surfaces of bones used in the snail experiment is unknown. Given that we were unaware of the presence of the flies and their larvae, meaning that there were so few of them we did not observe them, we think that their contribution to the modification of the bones was negligible. The damage pattern created by *Achatina* sp. was observed in a second uncontaminated experiment conducted with garden snails, where the same types of damage were recorded with similar frequencies (Figure 18.24).

Garden Snail (Helicidae)

Helix aspersa

A bone modification experiment was conducted in 2012 with 20 *Helix aspersa* in a tank with inert palm peat, from January to June, which is austral summer into winter. Twelve pieces of bone were added to the tank, and they were either fresh with soft tissue attached or dry. After four months, garden snails modified fresh and dry bone in equal frequencies. They made individual striations on half of the specimens and multiple parallel striations on all of them (Figure 18.25a, b). Nearly all of the specimens had pits with smooth bases (Figure 18.25c, d), probably produced by the acidic secretion of the foot. A few specimens had pitted surfaces and were polished, and one showed destruction. Etching (Figure 18.25b, c) and dissolution were recorded on more than half of the specimens, and all of them evidenced surface removal (Figure 18.24). Surface modifications most likely relate to the extraction of calcium, and consumption of protein-rich microbial colonies and tissue on fresh bones.

Discussion and Conclusions

Fourteen types of surface modifications were identified in the course of data collection on bones modified by various invertebrates in 12 experiments. Except for woodlice, all the taxa used in our experiments made individual striations and pitted the bone surfaces.

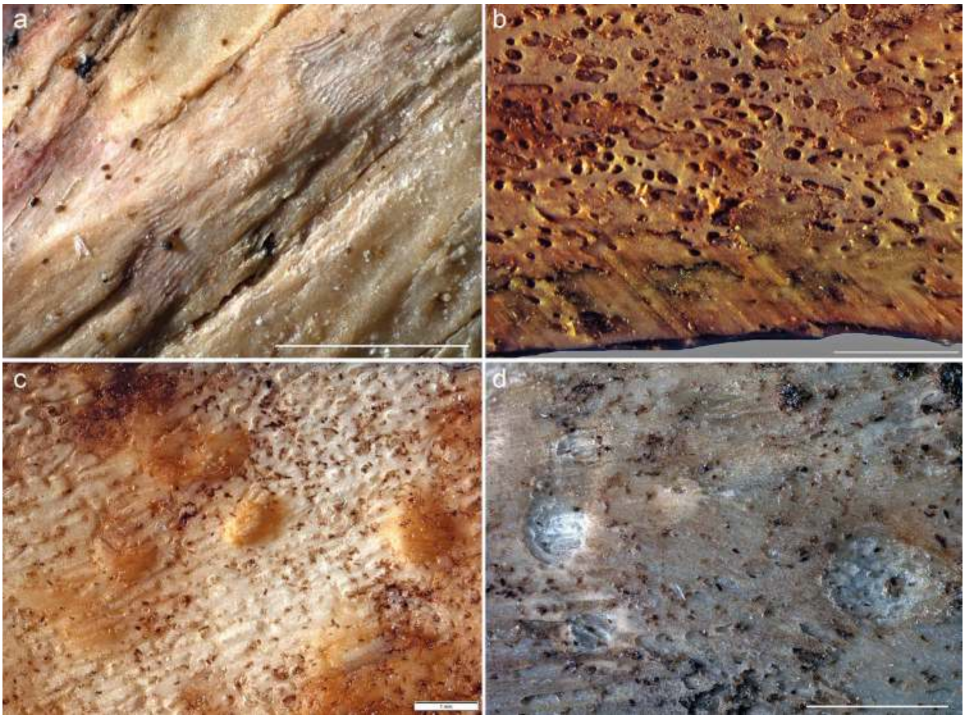

Figure 18.25 Damage made by garden snails (*Helix aspersa*) to bones used in an experiment. (a) Multiple parallel striations on a dry bird long bone, and (b) along the edge of a dry bovid rib. (c) Smooth-based pits on a fresh sheep long bone fragment and (d) a fresh bird femur. Note the etched surface appearance in (b) and (c). Scale in a = 10 mm, scales in b, c = 1 mm, scale in d = 2 mm. ([c] Reprinted from Dirks et al. 2015:19, Copyright [2015], with permission from eLife Sciences Publications Ltd. Creative Commons Attribution License https://creativecommons.org/licenses/by/4.0/.)

Multiple parallel striations were common to all taxa, as was etching and surface removal. At the end of the experiments only two bone flakes were unmodified, one from the termite experiment and the other from the fly experiment, and both were dry medium-size mammal pieces of cortical bone. There is overlap in the damage caused by termites, ants, and tenebrionid and trogid beetles. Discriminating between some taxa is thus difficult with the data at hand. The bone surface modifications made by a snail radula are perhaps the most distinct of the features observed, but without additional data on their size, spacing, and location, the multiple parallel striations created by a radula fall into the same general category as those made by ants, fly larvae, and woodlice, all of which present quite differently. Quantifiable information on pit size, individual striation size, shape, and orientation, and a more detailed characterization of different kinds of multiple parallel striations, and whether they occurred on surfaces or edges, would help in distinguishing between the damage patterns made by different invertebrate taxa. Future research on invertebrate modification of bone should also extend the length of bone exposure to a year, in order to capture a stronger taphonomic signature.

In all of the 12 experiments conducted with invertebrates, some of which are classified as herbivores, the agents modified dry bone as often as they did fresh bone with tissue attached. In this regard trogid beetles, for example, which normally visit carcasses in late stages of decomposition, are thus not necessarily good indicators of postmortem interval. Most of the fresh bone specimens used in the experiments developed fungal colonies and microbial communities on their surfaces, which were harvested by the invertebrates. While intentional surface gnawing of bone is clearly observed on some specimens, on others it may be incidental, resulting from the harvesting of microbes, which, as in the case of fungal hyphae, penetrate subsurface. It is unclear to what extent microbial colonies etched the surfaces of bones, but from our observations we would say that it is significant, especially on fresh chicken femora with tissue attached. More than half of all specimens used in the 12 experiments showed an etched surface appearance, except for fly larvae, which etched only one bone. While termites, ants, and snails may have etched the bone surfaces with acidic enzymes, we speculate that microbial activity accounts for much of the etched appearance on the experimental specimens.

Even under controlled laboratory conditions, and using well-fitting fine mesh lids to cover the tanks, two of the experiments were contaminated with latrine flies. The contamination was only evident once the bones were retrieved at the end of the experiments, when tiny fly puparia were observed on bone specimens at low magnification. This highlights not only the value of microscopy in the study, but also that multiple agents probably modify any given bone, at the same time or in succession. In the case of social insects like termites or ants, the damage that they cause to bone will probably be the only signature on the bones. In a natural setting and depending on the environment, however, it is more likely that a suite of invertebrates such as flies and their larvae, beetles, and woodlice modify the same bone.

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References

Anderson, G. S. (2001) Insect succession on carrion and its relationship to determining time of death. In *Forensic Entomology: The Utility of Arthropods in Legal Investigations* ed. by J. H. Byrd and J. L. Castner, pp. 143–175. CRC Press, Boca Raton, FL.

Anderson, G. S. (2010) Factors that influence insect succession on carrion. In *Forensic Entomology: The Utility of Arthropods in Legal Investigations* (2nd ed.) ed. by J. H. Byrd and J. Castner, pp. 201–250. CRC Press, Boca Raton, FL.

Backwell, L. R., J.-B. Huchet, T. Jashashvili, P. Dirks, and L. R. Berger (2020) Termites and necrophagous insects associated with early Pleistocene (Gelasian) *Australopithecus sediba* at Malapa, South Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 560:109989.

Backwell, L. R., A. Parkinson, E. Roberts, F. d'Errico, and J.-B. Huchet (2012) Criteria for identifying bone modification by termites in the fossil record. *Palaeogeography, Palaeoclimatology, Palaeoecology* 337–338:72–87.

Beal, R. S. (1991) Dermestidae (Bostrichoidea) (including Thorictidae, Thylodriidae). In *Immature Insects* (Vol. 2) ed. by F. W. Stehr, pp. 434–439. Kendall/Hunt. Dubuque, IA.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Paleobiology* 4(2):150–162.

Behrensmeyer, A. K., K. D. Gordon, and G. T. Yanagi (1989) Nonhuman bone modification in Miocene fossils from Pakistan. In *Bone Modification* ed. by R. Bonnichsen and M. H. Sorg, pp. 99–120. The Center for the Study of First Americans, Orono, ME.

Berger, L. R., D. J. de Ruiter, S. E. Churchill, P. Schmid, K. J. Carlson, P. H. G. M. Dirks, and J. M. Kibii (2010) *Australopithecus sediba*: A new species of *Homo*-like australopith from South Africa. *Science* 328(5975):195–204.

Berger, L. R., J. Hawks, D. J. de Ruiter, S. E. Churchill, P. Schmid, L. K. Delezene, T. L. Kivell, H. M. Garvin, S. A. Williams, J. M. DeSilva, and M. M. Skinner (2015) *Homo naledi*, a new species of the genus *Homo* from the Dinaledi Chamber, South Africa. *eLife* 4:e09560. DOI: 10.7554/eLife.09560.

Bolton, B., G. Alpert, P. S. Ward, and P. Nasrecki (2006) *Bolton's Catalogue of Ants of the World*. Harvard University Press, Cambridge, MA, (CD-ROM).

Britt, B. B., R. D. Scheetz, and A. Dangerfield (2008) A suite of dermestid beetle traces on dinosaur bone from the Upper Jurassic Morrison Formation, Wyoming, USA. *Ichnos* 15(2):59–71.

Byrd, J. H., and J. L. Castner (2001) Insects of forensic importance. In *Forensic Entomology: The Utility of Arthropods in Legal Investigations* ed. by J. H. Byrd and J. L. Castner, pp. 39–126. CRC Press, Boca Raton, FL.

Byrd, J. H., and J. K. Tomberlin (2001) Laboratory rearing of forensic insects. In *Forensic Entomology: The Utility of Arthropods in Legal Investigations* ed. by J. H. Byrd and J. L. Castner, pp. 177–200. CRC Press, Boca Raton, FL.

Coe, M. (1980) The role of modern ecological studies in the reconstruction of paleoecology in sub-Saharan Africa. In *Fossils in the Making* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 55–67. University of Chicago Press, Chicago.

Danielson, D. (2005) Bioarchaeological implications concerning the effects of termites (Isoptera) on human osseous remains. Poster presented at the *70th Annual Meeting of the Society for American Archaeology*, Salt Lake City, UT, 31 March 2005.

Danielson, D. (2006) Bioarchaeological implications concerning the effects of termites (Isoptera) on human osseous remains recovered in Papua New Guinea and the Socialist Republic of Vietnam. Poster presented at the *71st Annual Meeting of the Society for American Archaeology*, San Juan, Puerto Rico, 28 April 2006.

De Souza, A. M., and A. X. Linhares (1997) Diptera and Coleoptera of potential forensic importance in southeastern Brazil: relative abundance and seasonality. *Medical and Veterinary Entomology* 11(1):8–12.

Dekeirsschieter, J., F. Verheggen, G. Lognay and E. Haubruge (2011) Large carrion beetles (Coleoptera, Silphidae) in Western Europe: A review. *Biotechnology, Agronomy, Society and Environment* 15(3):435–447.

Derry, D. E. (1911) Damage done to skulls and bones by termites. *Nature* 86:245–246.

Dirks, P. H. G. M., J. M. Kibii, B. F. Kuhn, C. Steininger, S. E. Churchill, J. D. Kramers, R. Pickering, D. L. Farber, A.-S. Mériaux, A. I. R. Herries, G. C. P. King, and L. R. Berger (2010) Geological setting and age of *Australopithecus sediba* from southern Africa. *Science* 328(5975):205–208.

Dirks, P. H. G. M., L. R. Berger, E. M. Roberts, J. D. Kramers, J. Hawks, P. S. Randolph-Quinney, M. Elliott, C. M. Musiba, S. E. Churchill, D. J. de Ruiter, P. Schmid, L. R. Backwell, G. A. Belyanin, P. Boshoff, K. L. Hunter, E. M. Feuerriegel, A. Gurtov, J. Harrison, R. Hunter, A. Kruger, H. Morris, T. V. Makhubela, B. Peixotto, and S. Tucker (2015) Geological and taphonomic evidence for deliberate body disposal by the primitive hominin species *Homo naledi* from the Dinaledi Chamber, South Africa. *eLife* 4:e09561. DOI: 10.7554/eLife.09561.

Dirrigl, F. J., and L. Perrotti (2014) Taphonomic study of Japanese quail (*Coturnix japonica*) bone modification resulting from the burial and feeding behavior of the American burying beetle (*Nicrophorus americanus*). *International Journal of Osteoarchaeology* 24(3):272–278.

Fernández-Jalvo, Y., and M. D. M. Monfort (2008) Experimental taphonomy in museums: Preparation protocols for skeletons and fossil vertebrates under the scanning electron microscopy. *Geobios* 41(1):157–181.

Fernández-Jalvo, Y., and P. Andrews (2016) *Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification*. Springer, Dordrecht.

Freymann, B. P., S. N. de Visser, E. P. Mayemba, and H. Olff (2007) Termites of the genus *Odontotermes* are optionally keratophagous. *Ecotropica* 13(2):143–147.

Gabel, H. H. (1955) Beitrag zur kenntnis der biologie des speckkäfers *Dermestes vulpinus* F. *Zeitschrift für Angewandte Entomologie* 37(2):153–191.

Gentry, A. W. (1987) Pliocene Bovidae from Laetoli. In *Laetoli: A Pliocene Site in Northern Tanzania* ed. by M. D. Leaky and J. M. Harris, pp. 378–408. Clarendon Press, Oxford.

Gifford-Gonzalez, D. (2018) Invertebrate, plant, and geological effects on bone. In *An Introduction to Zooarchaeology* ed. by D. Gifford-Gonzalez, pp. 339–366. Springer, Cham, Switzerland.

Gładykowska-Rzeczycka, J. J., and M. Parafiniuk (2001) Atypical cranial vault and cervical vertebrae lesions caused by insects. *Journal of Paleopathology* 13(2):75–78.

Go, M. C. (2018) A case of human bone modification by ants (Hymenoptera: Formicidae) in the Philippines. *Forensic Anthropology* 1(2):117–123.

Háva, J. (2018) *World Catalogue of Dermestidae* (3rd ed.). Electronic document, http://www.dermestidae.wz.cz, accessed 13 January 2021.

Haynes, G. (1991) Noncultural modifications to mammalian bones in sites of mass deaths and serial predation. *Anthropologie* 29(3):151–156.

Heaton, V., C. Moffatt, and T. Simmons (2014) Quantifying the temperature of maggot masses and its relationship to decomposition. *Journal of Forensic Sciences* 59(3):676–682.

Hefti, E., U. Trechsel, H. Rüfenacht, and H. Fleisch (1980) Use of dermestid beetles for cleaning bones. *Calcified Tissue International* 31(1):45–47.

Herbert, D., and R. Kilburn (2004) *Field Guide to the Land Snails and Slugs of Eastern South Africa*. Natal Museum, Pietermaritzburg, South Africa.

Hill, A. P., and A. K. Behrensmeyer (1980) Early postmortem damage to the remains of some contemporary East African mammals. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology* ed. by A. K. Behrensmeyer and A. P. Hill, pp. 131–152. University of Chicago Press, Chicago.

Hillerton, J. E., B. Robertson, and J. Vincent (1984) The presence of zinc or manganese as the predominant metal in the mandibles of adult, stored-product beetles. *Journal of Stored Products Research* 20(3):133–137.

Hinton, H. E. (1945) *A Monograph of the Beetles Associated with Stored Products* (Vol. 1). British Museum (Natural History), London.

Holden, A. R., J. M. Harris, and R. M. Timm (2013) Paleoecological and taphonomic implications of insect damaged Pleistocene vertebrate remains from Rancho La Brea, Southern California. *PLoS ONE* 8(7):e67119. DOI: 10.1371/journal.pone.0067119.

Huchet, J.-B. (2014) Approche ichnologique et taphonomique des altérations ostéolytiques dues aux insectes en contexte archéologique. In *Manuel de Taphonomie* ed. by C. Denys and M. Patou-Mathis, pp. 185–207. Muséum National d'Histoire Naturelle CNRS, Paris.

Huchet, J.-B. (2017) Paléoentomologie, ichnologie et taphonomie. In *TaphonomieS* ed. by J.-Ph. Brugal, pp. 437–449. Collection Sciences Archéologiques. Edition des Archives Contemporaines, Paris.

Huchet, J.-B., D. Deverly, B. Gutierrez, and C. Chauchat (2011) Taphonomic evidence of a human skeleton gnawed by termites in a Moche-civilisation grave at Huaca de la Luna, Peru. *International Journal of Osteoarcheology* 21(1):92–102.

Ingrisch, S. (2011) Order Orthoptera Oliver, 1789. In *Animal Biodiversity: An Outline of Higher-Level Classification and Survey of Taxonomic Richness* ed. by Z. Q. Zhang. Zootaxa (special issue), 3148, pp. 195–197. Magnolia Press, Auckland, New Zealand.

Kaiser, T. M. (2000) Proposed fossil insect modification to fossil mammalian bone from Plio-Pleistocene hominid bearing deposits of Laetoli (Northern Tanzania). *Annals of the Entomological Society of America* 93(4):693–700.

Klass, K. D., and R. Meier (2006) A phylogenetic analysis of Dictyoptera (Insecta) based on morphological characters. *Entomologische Abhandlungen* 63(1–2):3–50.

Matu, M., I. Crevecoeur, and J.-B. Huchet (2017) Taphonomy and paleoichnology of Olduvai Hominid 1 (OH1), Tanzania. *International Journal of Osteoarchaeology* 27(5):785–800.

McFarlane, J. A. (1971) The carnivorous beetles of the Ithundu caves, Kenya. *Studies in Speleology* 2(1):149–158.

Palestrini, C., E. Barbero, and M. Zunino (1992) Biology of the preimaginal stages in trogid beetles (Coleoptera): Experimental data. *Bolletino di Zoologia* 59(1):69–71.

Parkinson, A. H. (2012) Dermestes maculatus *and* Periplaneta americana*: Bone Modification Criteria and Establishing their Potential as Climatic Indicators*. M.Sc. Dissertation, University of the Witwatersrand, South Africa.

Parry, N. J., M. W. Mansell, and C. W. Weldon (2016) Seasonal, locality, and habitat variation in assemblages of carrion-associated Diptera in Gauteng Province, South Africa. *Journal of Medical Entomology* 53(6):1322–1329.

Peacock, E. R. (1993) Adults and larvae of hide, larder and carpet beetles and their relatives (Coleoptera: Dermestidae) and of derodontid beetles (Coleoptera: Derodontidae). In *Handbooks for the Identification of British Insects* 5, Part 3, pp. 1–144. Royal Entomological Society of London.

Peck, S. B. (2000) Silphidae Latreille, 1807. In *American Beetles, Volume 1: Archostemata, Myxophaga, Adephaga, Polyphaga: Staphyliniformia* ed. by R. H. Arnett, Jr. and M. C. Thomas, pp. 268–271. CRC Press, Boca Raton, FL.

Pittoni, E. (2009) Necropoli of Pill'e Matta Quartucciu (Cagliari, Sardinia): Wild bee and solitary wasp activity and bone diagenetic factors. *International Journal of Osteoarchaeology* 19(3):386–396.

Pollak, S., and C. Reiter (1988) Maggot-induced postmortem changes simulating gunshot wounds. *Archiv fur Kriminologie* 181(5–6):146–154.

Roberts, E., R. R. Rogers, and B. Z. Foreman (2003) An experimental approach to identifying and interpreting dermestid (Insecta, Coleoptera) bone modification. *Journal of Vertebrate Paleontology* 23(3):89A–90A.

Robinson, G. S. (2019) Tineidae NHM: Global Taxonomic Database of Tineidae (Lepidoptera) (version 9.0, Nov 2011). In *Species 2000 & ITIS Catalogue of Life, 25th March 2019* ed. by Y. Roskov, G. Ower, T. Orrell, D. Nicolson, N. Bailly, P. M. Kirk, T. Bourgoin, R. E. DeWalt, E. Decock, E. van Nieukerken, J. Zarucchi, and L. Penev. Electronic document, www.catalogueoflife.org/col, accessed 16 January 2021. Species 2000: Naturalis, Leiden, the Netherlands.

Roth, L. (2003) Systematics and phylogeny of cockroaches (Dictyoptera: Blattaria). *Oriental Insects* 37(1):1–186.

Scheffrahn R. H., and J.-B. Huchet (2010) A new termite species (Isoptera: Termitidae: Termitinae: *Amitermes*) and first record of a subterranean termite from the Coastal Desert of South America. *Zootaxa* 2328:65–68.

Schroeder, H., H. Klotzbach, L. Oesterhelweg, and K. Püschel (2002) Larder beetles (Coleoptera, Dermestidae) as an accelerating factor for decomposition of a human corpse. *Forensic Science International* 127(3):231–236.

Schultz, T. R. (2000) In search of ant ancestors. *Proceedings of the National Academy of Sciences of the United States of America* 97(26):14028–14029.

Shear, W. (2011) Class Diplopoda de Blainville in Gervais, 1844. In *Animal biodiversity: An Outline of Higher-Level Classification and Survey of Taxonomic Richness* ed. by Z. Q. Zhang. *Zootaxa* (special issue), 3148, pp. 159–164. Magnolia Press, Auckland, New Zealand.

Soldati, F. (2007) Coleoptera Tenebrionidae (Alleculinae excluded), Systematic catalogue and atlas. *Mémoires de la Société Linnéenne de Bordeaux* 6:1–186.

Tappen, M. (1994) Bone weathering in a tropical rain forest. *Journal of Archaeological Science* 21(5):667–673.

Thorne, B. L., and R. B. Kimsey (1983) Attraction of Neotropical *Nasutitermes* termites to carrion. *Biotropica* 15(4):295–296.

Timm, R. M. (1982) Dermestids. *Field Museum of Natural History Bulletin* 53:14–18.

Val, A., P. H. Dirks, L. R. Backwell, F. d'Errico, and L. R. Berger (2015) Taphonomic analysis of the faunal assemblage associated with the hominins (*Australopithecus sediba*) from the early Pleistocene cave deposits of Malapa, South Africa. *PLoS ONE* 10(6):e0126904. DOI: 10.1371/journal.pone.0126904.

Vanin, S., and J.-B. Huchet (2017) Forensic entomology and funerary archaeoentomology. In *Taphonomy of Human Remains: Forensic Analysis of the Dead and Depositional Environment* ed. by E. Schotsmans, N. Márquez-Grant, and S. Forbes, pp. 167–186. Wiley-Blackwell, Chichester, UK.

Watson, J. A. L., and H. M. Abbey (1986) The effects of termites (Isoptera) on bone: Some archaeological implications. *Sociobiology* 11(3):245–254.

Wesener T., M. J. Raupach, and P. Sierwalda (2010) The origins of the giant pill-millipedes from Madagascar (Diplopoda: Sphaerotheriida: Arthrosphaeridae). *Molecular Phylogenetics and Evolution* 57(3):1184–1193.

Wesener, T. (2014) A new phylogenetic analysis of the Sphaerotheriida (Diplopoda) with a revision of the Australian giant pill-millipedes. *Invertebrate Systematics* 28(2):196.

Wood, W. B. (1976) The skeletal material from the Brooloo Range and Rocky Hole Creek burial sites. *Archaeology and Physical Anthropology in Oceania* 11(3):175–185.

Wylie, F. R., G. L. Walsh, and R. A. Yule (1987) Insect damage to aboriginal relics at burial and rock-art sites near Carnarvon in central Queensland. *Journal of the Australian Entomological Society* 26(4):335–345.

Zacher, F. (1927) *Die Vorrats-, Speicher- und Materialschädlinge und ihre Bekämpfung.* Parey, Berlin.

Zanetti, N. I., A. A. Ferrero, and N. D. Centeno (2019) Depressions of *Dermestes maculatus* (Coleoptera: Dermestidae) on bones could be pupation chambers. *The American Journal of Forensic Medicine and Pathology* 40(2):122–124.

Zanetti, N. I., E. C. Visciarelli, and N. D. Centeno (2014) Taphonomic marks on pig tissue due to cadaveric Coleoptera activity under controlled conditions. *Journal of Forensic Sciences* 59(4):997–1001.

Reptile Taphonomy

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Contents

> Your serpent of Egypt is bred now of your mud by the
> operation of your sun: so is your crocodile.
>
> **—William Shakespeare**
> *Antony and Cleopatra,* Act II, Scene 7

Introduction and Forensic Relevance

While not as prevalent on bones as the taphonomic effects of carnivores, rodents, and other mammals (see Chapter 9, this volume), reptiles can cause significant alterations to human remains. Crocodilians/crocodylians (i.e., crocodiles, alligators, caimans, and their relatives in the Order Crocodilia) are the extant reptiles with potential to do the most damage to bone during initial prey capture and feeding or through scavenging.

Whether a crocodilian attack is fatal or not correlates somewhat with the size of the attacking animal and if the intended victim was in the water (Fukuda et al. 2015). Bites, especially from smaller crocodilians, can be minor and survivable (Fukuda et al. 2015; Hertner 2006; Shepherd and Shoff 2014), but traumatic amputation often results from the bites of larger individuals, frequently leading to death quickly or more slowly through later sepsis, with drowning of a secured victim also a common cause (Fukuda et al. 2015;

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Haddad and Fonseca 2011; Harding and Wolf 2006; Langley 2005; Wolf and Harding 2014). American alligator (*Alligator mississippiensis*) bites (including non-fatal attacks) are most often on the extremities but can appear on the head and torso (Langley 2005, 2010). Crocodilian attacks may occur on land or in water, with the latter being much more common (Florida Fish and Wildlife Conservation Commission 2019a; Langley 2010; Sinton and Byard 2016). I instances of attacks by climbing into boats or upon occupants of tents are known (Caldicott et al. 2005; Gruen 2009).

Fatal alligator attacks on humans are uncommon in the USA and average one per year, likely due in part to natural mutual avoidance; in comparison, snake bites and vehicle-moose collisions both have an estimated average of six fatalities per year (Conover 2019). Alligator encounters appear to be on the increase, likely caused by the rebounding of their populations due to previous endangered species protection (Langley 2005, 2010; Woodward et al. 2019). In Florida, from 1948 (when record keeping began) to 2019, 413 unprovoked alligator bite incidents were recorded, 25 of which were fatal; over the preceding decade, Florida averaged seven unprovoked bites per year that were serious enough to require professional medical treatment (Florida Fish and Wildlife Conservation Commission 2019b). Some attacks may be due to the alligator having been desensitized to human proximity through illegal feeding or discarding food into a body of water populated by alligators (Harding and Wolf 2006; Langley 2010; Wolf and Harding 2014). Harding and Wolf (2006) reported three fatal cases in southwest Florida from alligator attacks and noted six additional cases of postmortem scavenging. In some cases of postmortem feeding, it is possible that alligators were used as a deliberate method of human body disposal. Attacks by American alligators peak during the warmer months of the year (Langley 2010; Woodward et al. 2019), although this may relate to human activity patterns. Attack rates by Nile crocodiles (*Crocodylus niloticus*) also vary seasonally; these patterns need to be studied further in order to decrease human fatalities from this source (Pooley 2015, 2016; Pooley et al. 1992).

Attacks on humans by other crocodilian species in other parts of the world have been documented and surpass the relative frequency of alligator attacks in the USA. Fatal attacks by Nile crocodiles are common in many countries in Africa (Pooley et al. 1992). Crocodiles are known to kill humans on a regular basis, for example, in southwestern Madagascar along the Mongoky River (Hart and Sussman 2008). Crocodilian attacks are also reported from India (Chattopadhyay et al. 2013) and Brazil (Haddad and Fonseca 2011). In northern Australia, fatalities from crocodile attack are not uncommon, with most attributed to the saltwater crocodile (*Crocodylus porosus*) (Caldicott et al. 2005; Fukuda et al. 2014, 2015; Gruen 2009; Sinton and Byard 2016; Westaway et al. 2011; Wood 2008). These may be expected to increase as this species's population rebounds. Close to 6000 "problem" saltwater crocodiles had to be relocated from 1977–2013 alone (Fukuda et al. 2014), so the potential for attacks is viewed as significant in this region.

The overall amount of trauma caused by saltwater crocodiles, often attaining the largest sizes (>5 m) among crocodilians in the world, can be quite severe (Gruen 2009; Mekisic and Wardill 1992; Wood 2008). Davidson and Solomon (1990) examined the remains of a man killed by a saltwater crocodile in Australia. Portions of the body were not consumed, and there was damage including tooth marks on the lower limbs of the individual. The legs of the victim had been torn from the torso and were found 10 meters from the bank of a river. Sinton and Byard (2016) noted that among the 11 saltwater crocodile fatalities they examined, in some cases trauma included the remains being incomplete and highly fragmented (including recovery of the bulk of remains as stomach contents), crushing/fracturing of the skull and thorax, avulsion of limbs, and decapitation. Tooth marks were noted in nine of these cases.

Fossil Taphonomic History

The Order Crocodilia and its antecedents have a long fossil history dating back to the late Permian, over 250 million years ago, and had high diversity by the Mesozoic (Grigg and Kirshner 2015). Species belonging to members of the extant crocodilian families evolved during the Cretaceous and survived the Cretaceous-Paleogene extinction event over 60 million years ago. Crocodilians as we know them today span the entirety of hominin evolution, and their taphonomic effects are relevant to paleontologists as well as forensic anthropologists. These species commonly evoke fear due to their status as dangerous predators that frequently come into contact with humans (Pooley 2015, 2016).

Some paleontological researchers have detected possible taphonomic effects from crocodilian feeding in the fossil record (Pobiner 2008). A complete turtle skeleton from the Upper Jurassic bears tooth marks along the posterior margin, some of which appear to be healed, that have been attributed to a broad-nosed crocodilian (Joyce 2000). Similar tooth marks on turtle shells from the Upper Jurassic are also attributed to predation by the broad-nosed crocodilian *Machimosaurus* (Meyer 1994). Botfalvai et al. (2014) found possible crocodilian tooth marks (pits with U-shaped profiles and circular to oval shapes and some associated striations) on a portion of chelonian anterior carapace adjacent to the head on a Late Cretaceous specimen from Hungary. These marks are similar to carnivore damage to chelonian carapaces from modern environments (Milàn et al. 2010). A species of crocodilian had similar tooth marks on its skull roof, some of which had a bisected morphology characteristic of modern crocodilians (see "Crocodilian Tooth Marks" section, below). The specimens may have been the prey of an additional crocodilian species known from this fossil locality. Boyd et al. (2013) found evidence of crocodyliform feeding on juvenile ornithischian dinosaur specimens from the Upper Cretaceous in Utah, including a partial tooth crown broken off in one tooth puncture, pits including one bisected mark, and associated hook scores. Noto et al. (2012) also found evidence of crocodilian feeding on chelonian and dinosaur bones from Cretaceous deposits in Texas, including pits (only one potentially bisected), hook scores, and a puncture. Fisher (1981a, b, c) assigned the origin of enamel-less teeth in some Wyoming Paleocene deposits to crocodilian digestion, although crocodile feces did not appear to be the origin of most of the faunal assemblage. Possible traces of crocodilian feeding appear on larger fossil mammal bones at least as far back as the Miocene (Mikuláš et al. 2006).

Crocodile feeding has been forwarded as a possible cause of death for multiple early hominin specimens due to their depositional contexts and tooth mark evidence. Davidson and Solomon (1990) noted possible crocodile-inflicted tooth marks to (Olduvai hominin) OH 7, the type specimen for *Homo habilis*. This damage is consistent with Nile crocodile, fossils of which have been found at Olduvai (Davidson and Solomon 1990). Crocodile feeding may have been involved in the demise of OH 8 and OH 35, the former of which has extensive tooth markings, including multiple bisected marks (Njau and Blumenschine 2012); the case for crocodile involvement with OH 35 is less clear (Aramendi et al. 2017; Baquedano et al. 2012). Scavenging of hominin remains in cases where crocodile involvement is determined is also a plausible scenario. Crocodile tooth marks have also been identified on other Plio-Pleistocene fossils, sometimes appearing similar to hominin butchery marks (e.g., Sahle et al. 2017).

Crocodilians

Crocodilian Species Worldwide

At least 25 species of crocodilians exist in the world today, and their ranges and environments can be found in Table 19.1 (Alderton 1991; Britton 2012; Grigg and Kirshner 2015; Somma 2021). Of these, two are native to the USA (Figure 19.1): American alligators (*Alligator mississippiensis*), family Alligatoridae, inhabit the southeastern USA; American crocodiles (*Crocodylus acutus*), family Crocodylidae, inhabit only the coastal areas of south Florida as well as parts of Central America (National Park Service 2017; US Fish and Wildlife Service 2021). American alligators are found in the wild in Texas, Oklahoma, Arkansas, Louisiana, Mississippi, Alabama, Florida, Georgia, South Carolina, and North Carolina, with the largest populations in Louisiana and Florida (Langley 2005; Somma 2021), and are sometimes kept as pets and/or released outside of this region (Shepherd and Shoff 2014). Spectacled caiman (*Caiman crocodilus*), an invasive species, has also established itself in southeastern Florida (Langley 2010; Somma and Fuller 2021). Crocodilians are generally found in tropical regions, but both the American alligator and Chinese alligator (*Alligator sinensis*) are relatively cold-tolerant and are found at the highest elevations and latitudes of any crocodilian species (Grigg and Kirshner 2015).

The annual thermal cycle in North America affects the physiology and growth cycle of alligators, which can also affect the number of attacks on humans during a particular time period. In southwest Louisiana, alligators stop feeding in October and do not resume feeding until late March or early April. During the warmer season, captive alligators can grow about 150 cm/year and reach sexual maturity in six years, while wild alligators grow 30 cm/year on average and reach sexual maturity in ten years (National Park Service 2017).

Crocodilian Diet and Feeding

The diets of crocodilian taxa vary due to factors such as snout shape and body size, the former of which evolved to adapt to different prey types and sizes, and by geographic location, habitat, and prey encountered. American alligators forage opportunistically and exhibit a varied diet, ranging from small insects and crustaceans to large vertebrates. Their prey includes fish, snails, birds, frogs, and mammals that venture near the water's edge (Grigg and Kirshner 2015; National Park Service 2017). As an American alligator increases in size, its diet becomes more diverse; juveniles tend to prey on invertebrates, whereas large adults prey more on vertebrates than invertebrates (Saalfeld 2010; Wallace and Leslie 2008). While fish are the most prevalent vertebrates in the diet of adult alligators, they also prey on terrestrial species. Crocodilians can be surprisingly mobile on land, lunging for short distances to ambush prey out of water and pursuing slower-moving prey (Caldicott et al. 2005).

The manner in which crocodilians consume their prey is similar throughout all species and usually follows a sequence of six stages: prey capture, killing, reduction,

Table 19.1 Extant Crocodilian Species by Family

Species	Binomial	Current Range	Environments
		Alligatoridae	
American alligator	*Alligator mississippiensis*	Southeastern USA, Texas though Florida	Freshwater (marshes, swamps, and rivers) and sometimes brackish
Chinese alligator	*Alligator sinensis*	China around the lower Yangtze River	Slow-moving freshwater rivers, streams, and ponds
Spectacled caiman	*Caiman crocodilus*	Central and South America; invasive in southern Florida	All lowlands, wetlands, and riverine systems
Broad-snouted caiman	*Caiman latirostris*	Northern Argentina, Bolivia, southeastern Brazil, Paraguay, Uruguay	Freshwater and brackish mangroves, marshes, and swamps
Yacare caiman	*Caiman yacare*	Northern Argentina, southern Brazil, southern Bolivia, Paraguay	Wetlands, rivers, and lakes
Black caiman	*Melanosuchus niger*	The Amazon basin, including Brazil, Guyana, Peru, and Bolivia	Freshwater riverine systems and other slow-moving waters
Cuvier's dwarf caiman	*Paleosuchus palpebrosus*	The Amazon basin including Bolivia, Brazil, Colombia, Ecuador, French Guiana, Guyana, Peru, Surinam, Venezuela	Freshwater forested ravine systems and flooded forests around larger lakes
Smooth-fronted caiman	*Paleosuchus trigonatus*	The Amazon basin including Brazil, Bolivia, Colombia, Ecuador, French Guiana, Guyana, Peru, Surinam, Venezuela	Forest streams
		Crocodylidae	
American crocodile	*Crocodylus acutus*	Central and South America; extreme south of Florida	Freshwater and brackish coastal habitats
Morelet's crocodile	*Crocodylus moreletii*	Belize, Guatemala, Mexico	Freshwater swamps and marshes in forested area
Cuban crocodile	*Crocodylus rhombifer*	Cuba	Freshwater swamps, some brackish
Orinoco crocodile	*Crocodylus intermedius*	The Orinoco basin, Colombia and Venezuela	Freshwater riverine systems
New Guinea crocodile	*Crocodylus novaeguineae*	Papua New Guinea, Irian Jaya	Freshwater swamps, lakes, and rivers; rarely coastal
Freshwater crocodile	*Crocodylus johnstoni*	Northern Australia	Freshwater river systems, lakes, and swamps; some brackish

(Continued)

Table 19.1 ***(Continued)*** **Extant Crocodilian Species by Family**

Species	Binomial	Current Range	Environments
Saltwater crocodile	*Crocodylus porosus*	Coastal areas from southern India to northern Australia, including SE Asia, Borneo, Myanmar, Indonesia, and Papua New Guinea	Brackish waters around coastal areas and inland along rivers; can travel in ocean
Philippine crocodile	*Crocodylus mindorensis*	Philippines	Freshwater lakes, ponds, and marshes
Siamese crocodile	*Crocodylus siamensis*	SE Asia and into Indonesia, much reduced from former range	Slow-moving freshwater swamps, lakes, and marshes
Mugger crocodile	*Crocodylus palustris*	Indian subcontinent and adjacent	Freshwater lakes, rivers, and marshes; artificial bodies of water
Slender-snouted crocodile	*Mecistops cataphractus*	Western Africa including the Congo basin and north	Riverine habitats with dense vegetation cover, some brackish
Nile crocodile	*Crocodylus niloticus*	Most of east and southern Africa and Madagascar, excluding north Africa, Sahara, and horn	Lakes, rivers, freshwater swamps, and brackish water; seawater-tolerant
West African Nile crocodile	*Crocodylus suchus* (formerly subspecies of *C. niloticus*)	Western to central Africa	Lakes, rivers, freshwater swamps, and brackish water; seawater-tolerant
Dwarf crocodile	*Osteolaemus tetraspis*	Western Africa	Permanent pools in swamps and areas of slow-moving freshwater in rain forests
Congo dwarf crocodile	*Osteolaemus osborni*	Congo	Permanent pools in swamps and areas of slow-moving freshwater in rain forests
		Gavialidae	
Gharial	*Gavialis gangeticus*	Northern Indian subcontinent and adjacent	Riverine systems, slower pools
False gharial	*Tomistoma schlegelii*	Indonesia, Malaysia, and Sarawak	Freshwater lakes, rivers, and swamps

Source: Alderton (1991), Britton (2012), and Grigg and Kirshner (2015).

Figure 19.1 Range of American alligator (*Alligator mississippiensis*) and the US portion of the range of American crocodile (*Crocodylus acutus*), overlapping in southern Florida. Southeastern Florida also has an established population of spectacled caiman (*Caiman crocodilus*) (not shown) overlapping with the two native species. (Data from Somma 2021, Somma and Fuller 2021, and US Fish and Wildlife Service 2021.)

defleshing, swallowing, and carcass abandonment (Cleuren and De Vree 2000; Njau and Blumenschine 2006). Crocodilians secure prey through the anterior portion of the jaws and rotate the head sideways so that the angle of approach brings one side of the jaws into contact with the prey. Small animals are repositioned in the mouth of a crocodilian in such a way that one powerful killing bite can be performed. The repositioning of the prey indicates inertial feeding behavior, a stereotypic form of prey transport which is utilized to move large food items from the jaw tips into and through the oral cavity. The head and neck are elevated, and the hyolingual apparatus presses the prey into the mouth. The expansive opening of the jaws draws the prey farther into the mouth cavity (Biknevicius and Ruff 1992; Njau and Blumenschine 2006). These bites can occur multiple times until the prey is killed or crushed.

If the prey is larger, further effort is required from the crocodilian. Repositioning the jaws is used to achieve a better grasp on the prey, and bringing the prey underwater can lead to drowning. "Death roll" behavior is common for crocodilians. It entails securing a portion of the prey in its jaws and initiating a violent rotation along the long axis of its body (Chattopadhyay et al. 2013; Drumheller and Brochu 2014; Grigg and Kirshner 2015; National Park Service 2017). Limbs are folded against the body, and the movement is accomplished through motions of the head, trunk, and tail (Fish et al. 2007).

Further bites are utilized to transport food into the throat once smaller prey is dead. For larger prey, crocodilians may require additional reduction before swallowing. Though the conical teeth of crocodilians are important for grasping prey, they are not well adapted to cut or tear into soft tissue. Lateral thrashing has been observed in crocodilians as a means to tear smaller portions off of a prey item (Drumheller and Brochu 2014), similar

Figure 19.2 Nile crocodiles (*Crocodylus niloticus*) feeding on a Cape buffalo (*Syncerus caffer*) in the Kruger National Park, South Africa.

to shark feeding behavior (Chapter 7). Large prey reduction and defleshing can continue until an entire carcass is consumed (Figure 19.2). Dismemberment can disperse elements, which are then discarded and abandoned (Davidson and Solomon 1990; Wood 2008). For example, turtle shell remnants are often abandoned once the majority of soft tissues have been consumed (Milàn et al. 2010).

The bite force of crocodilians can be very high and has been measured at over three times stronger than that of the avid bone-crushing spotted hyena, *Crocuta crocuta* (Erickson et al. 2012; Chapter 9). Crocodilian bite force also has been shown to scale linearly with animal size (Erickson et al. 2004; 2012). Erickson et al. (2004) found that captive American alligators bite more forcefully than their wild counterparts due to their larger size, broader heads, shortened jaws, and greater body mass, so bite mark studies on captive specimens can be problematic. This high bite force attained, combined with the dentition of crocodilians, is sufficient to cause a wide variety of bone damage (see below).

Digestive Processes

Since crocodilians gulp their food in large pieces, their digestive system is complex. Diefenbach (1975a, b) observed the rate of gastric function of spectacled caiman (*Caiman crocodilus*) relative to temperature. Sixteen small, medium, and large caimans were used. The animals were fed at 15°C, 20°C, 25°C, and 30°C (Diefenbach 1975a). It took four to five days for the caimans to digest their food completely at 30°C, but at 15°C it took more than fourteen days.

The digestive system of crocodilians, including American alligators, is highly acidic. Fisher (1981a) conducted feeding experiments that involved four individuals each of American alligator and spectacled caiman that were fed rats and mice. He found that teeth recovered from feces were usually isolated and enamel-less due to decalcification. Features of bones were subdued and more difficult to recognize. Preserved organic matrices sometimes retained their histologic structure, though signs of bacterial decomposition may have begun to show (Fisher 1981a). Wood (2008) reported human remains that were recovered from a saltwater crocodile's stomach 25 days after the fatal attack occurred. The articular ends of the long bones had been destroyed, and their shafts had extensive thinning, with some softening and curling. The bones could still be identified as human from their gross morphology. Keratinized tissues (nails, hair, etc.) survived the digestion process more robustly than cortical bone.

Crocodilian Tooth Marks

Multiple actualistic studies of crocodilian bone-modifying behaviors and their diagnostic traces have been conducted (e.g., Baquedano et al. 2012, Delaney-Rivera et al. 2009, Milàn et al. 2010; Njau and Blumenschine 2006; Njau and Gilbert 2016; Schneider 2018; Westaway et al. 2011). Many marks produced by crocodiles are individually indistinguishable from mammalian carnivores, but some crocodilian marks are more diagnostic, and the overall damage patterns differ. (See Table 19.2 for a summary of crocodilian tooth marks and Chapter 9 for mammalian tooth mark terminology.)

Alligators have 74 to 80 teeth in their mouth at a time, and as the teeth wear down, they are replaced, typically by larger teeth as the individual ages (Enax et al. 2013; Njau and Blumenschine 2006; Poole 1961). An alligator can go through 3000 teeth in a lifetime (National Park Service 2017); Poole (1961) estimated that a large, adult Nile crocodile would have replaced each tooth 45 times. Crocodilian tooth shape also affects the type of marks that they leave on bone. While terrestrial mammalian carnivores have distinctly heterodont teeth adapted to different functions, those of crocodilians are relatively homodont (uniform). There are some differences among their teeth, which show a gradual change in form from anterior (sharper, caniniform) to posterior (more rounded, molariform) (D'Amore et al. 2019). The size of teeth also varies upon location in the mouth and by species, and the *carinae* (sharp ridges on conical teeth; Figure 19.3) are more prominent and sharper on the anterior teeth (Poole 1961).

When a recently erupted, unworn tooth is involved in a bite, the carinae may leave a "bisected" mark (Drumheller and Brochu 2014). Some pits caused by crocodilians are partly or entirely bisected by a sharp linear depression that can exceed the diameter of the pit, resulting in a V-shaped cross-section. This type of tooth mark has not been identified in any mammalian group and is considered to be potentially diagnostic for crocodilians. Crocodilian tooth marks can occur anywhere on any bone, though the marks are commonly observed on remains that have been stripped of soft tissue. Most affected bones from crocodile-modified assemblages typically have only one or a few tooth marks visible (see "Case Study" section, below). Without context, however, isolated crocodilian modifications are frequently indistinguishable from those made by other agents (Njau and Gilbert 2016; Sala et al. 2014; Sala and Arsuaga 2013). Tooth marks and other damage may occur to bone during all stages of feeding and may be found on bones that were abandoned after feeding (Njau and Blumenschine 2006). Edge polish is characteristic of mammalian carnivores (Chapter 9) and not observed on crocodilian tooth mark morphology. Though bones are typically ingested, crocodilians do not seek out bone marrow as a source of nutrition and therefore do not produce tooth marks while specifically gnawing in order to access the stored fat reserves from the epiphyses as mammalian carnivores do.

Table 19.2 Tooth Mark Morphology Comparison Between Mammalian Carnivores and Crocodilians

Tooth Mark (see Chapter 9)	Mammalian Carnivores	Crocodilians
Pits	Circular to angular and range from around 1.5–4.0 mm. Internal surface crushed; can be isolated or associated with other tooth marks.	Circular to angular depressions that do not penetrate cortical bone. Some pits are bisected by a sharp linear depression. Pit diameters can range from 0.1–6.0 mm or more. Associated with crushing, grasping, and holding between teeth.
Scores/Striations	Linear, may angle from a well-defined pit, and lengths range from 3.0–13.0 mm. U-shaped cross sections, and variable orientation to long bone axis, though tending towards transverse. Internal surface crushed; can be isolated or associated with other tooth marks.	Linear impressions in bone ranging from superficial to deep that do not penetrate cortical bone. May be described as drag-snags and hook scores. “Drag-snag” describes a patterned mark with a pit and associated striae. Associated with torsional forces applied against incompletely gripped bones that slip on clasped jaws. Hook scores are L or J-shaped. Hook scores may contain internal parallel and sub-parallel striations within the mark. Lengths range from 3.5–55.0 mm.
Punctures	Circular to oval, semicircular notches at fracture edges and diameter ranges from 2.0–7.5 mm. Bowl-shaped cross sections. Usually occur on cancellous bone, with thin cortical bone depressed into trabeculae.	Circular to oval and can penetrate through thick cortical bone. Serial puncturing may be observed. May be associated with chipping and shallow to deep cracks that run along the long axis of bone. Bisected punctures are sometimes observed. Diameters range from 1.0–11.0 mm.
Furrows	Linear with average length from 13.0–24.0 mm. U-shaped crossed sections, usually perpendicular to break edges. Usually occur on cancellous bone.	Furrows occasionally observed in American alligator assemblages. Linear tooth marks that may penetrate as deep as punctures though furrows are longer in length than width.
Fracturing	Can produce spiral breaks of long bone shafts, and fracture thin, flat portions of bones.	Sometimes noted. American alligators can cause spiral fractures in bones due to their aggressive style of feeding.

Source: Domínguez-Rodrigo and Piqueras (2003), Njau and Blumenschine (2006), Njau and Gilbert (2016), Schneider (2018), and Selvaggio and Wilder (2001).

Pits

Tooth pits (Figures 19.4 and 19.5) are rounded or jagged depressions in cortical bone that do not penetrate through it. All types of pits are associated with crushing, grasping, and holding between teeth. Rounded pits are often left behind due to teeth imposing extreme compressive force, and jagged pits typically lack morphology that can be related to tooth position (Njau and Gilbert 2016). As noted above, anterior crocodile teeth tend to leave partly or entirely *bisected pits*, in which the bisection is a sharp linear depression that may exceed the diameter of the main pit, resulting in a V-shaped cross section (Figures 19.5 and 19.6). Posterior teeth are more frequently worn down and leave more rounded pits (Njau and Gilbert 2016). The diameters of all pits typically range from 0.1 mm to over 6.0 mm (Njau and Blumenschine 2006), and the diameters of bisected pits typically range from 1.4–4.0 mm (Domínguez-Rodrigo and Piqueras 2003; Njau and Blumenschine 2006).

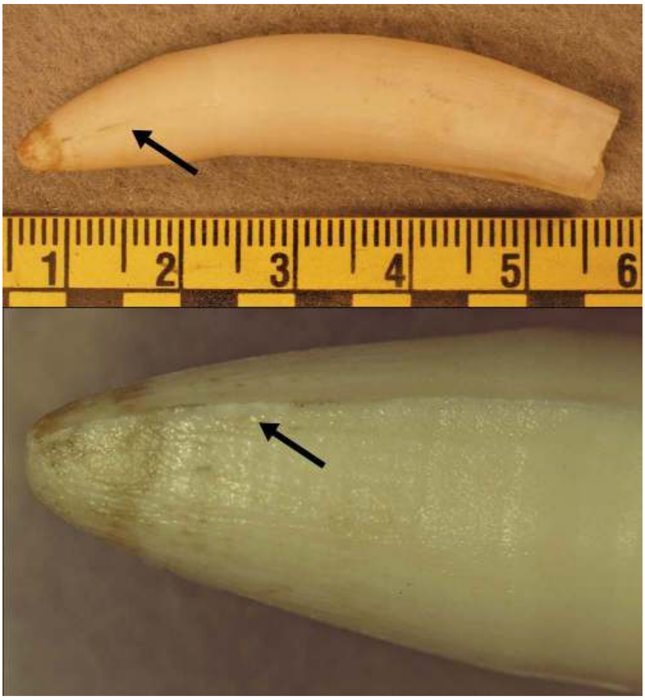

Figure 19.3 Tooth of American alligator (*Alligator mississippiensis*) showing carinae (ridges), which may leave distinctive marks in bone.

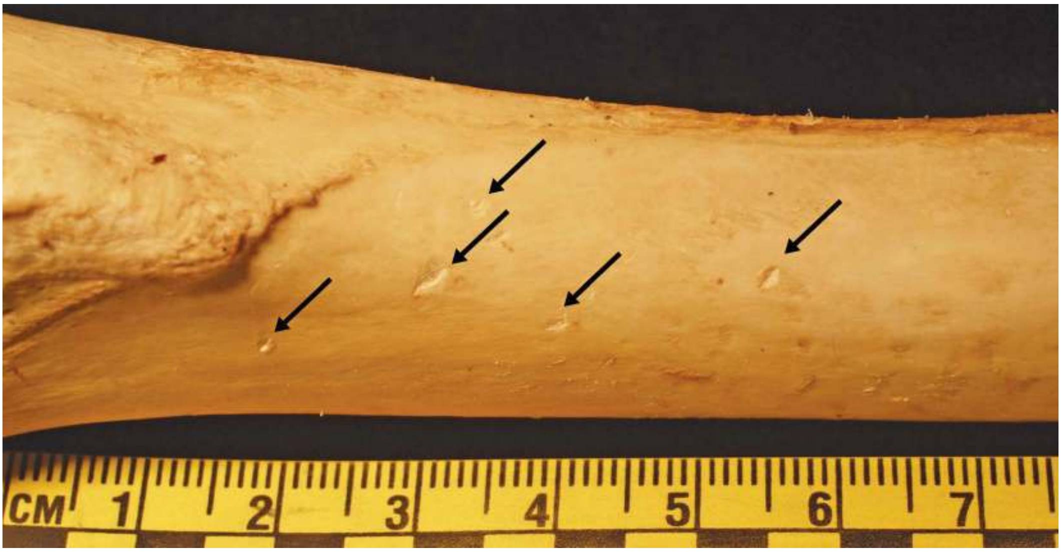

Figure 19.4 Pits on the diaphysis of white-tailed deer (*Odocoileus virginianus*) femur caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). Note the V-shaped bisections (arrows), diagnostic of crocodilians and not found among mammalian carnivores. The scale is in cm.

Figure 19.5 Scores (arrows) amid an area of pits on the diaphysis of a white-tailed deer (*Odocoileus virginianus*) femur caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). Note the bisections and snags on pits and scores on left side and middle; see also Figure 19.4. The scale is in cm.

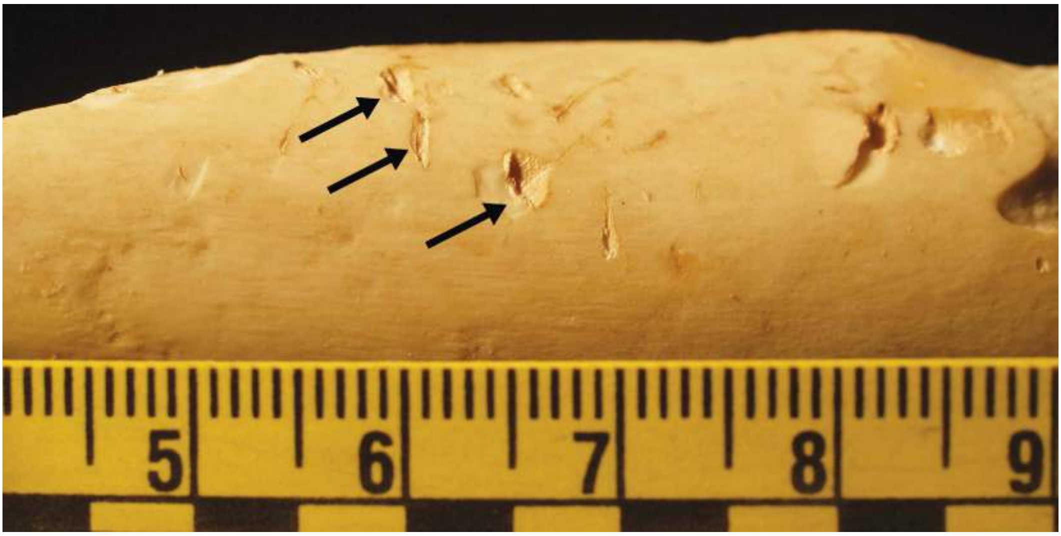

Figure 19.6 Bisected pits (arrows) on white-tailed deer (*Odocoileus virginianus*) long bone fragment caused by American alligator (*Alligator mississippiensis)* feeding (Schneider 2018). The scale is in cm.

Bisected pits left by Nile crocodiles will usually be observed on long bones and the postcranial axial skeleton (Boyd et al. 2013; Brochu et al. 2010; Njau and Blumenschine 2006; Noto et al. 2012; Rivera-Sylva et al. 2009). *Striation pivots* refer to tooth pits that also indicate a change in direction of the marks due to crocodilian feeding sequence and behaviors. Serial pitting, inflicted by adjacent teeth biting down on bone, occasionally may be observed.

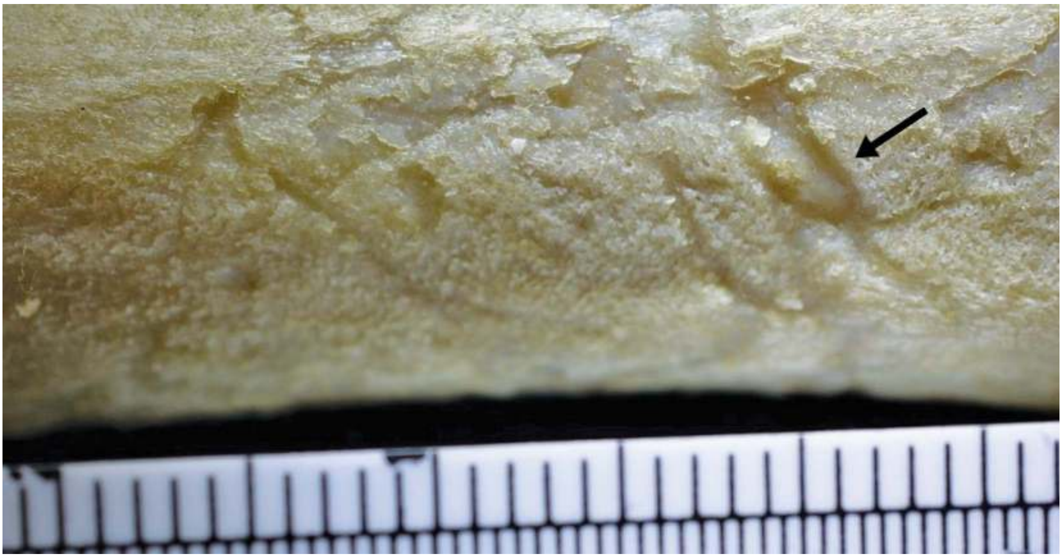

Figure 19.7 Hook scoring (arrow) on a pig (*Sus scrofa*) femur caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). The scale is in cm.

Scores

Scores (striations) are linear impressions in bone ranging from superficial to deep but not penetrating cortical bone (Figure 19.5). Microscopically, striations may have internal striae. *Hook scores* (Figures 19.7 and 19.8) are a special subcategory that is unique to crocodilian-modified assemblages (Njau and Blumenschine 2006, Njau and Gilbert 2016). Hook scores are L- or J-shaped and created when an impacting tooth changed direction abruptly during a single biting event (Njau and Blumenschine 2006). Hook scores often contain internal parallel and sub-parallel striations within the main mark. Hook scores typically range from 3.5–55.0 mm in length. The average length for tooth scores produced by mammalian

Figure 19.8 Hook scoring (arrow) on a pig (*Sus scrofa*) femur caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). Scale is in cm.

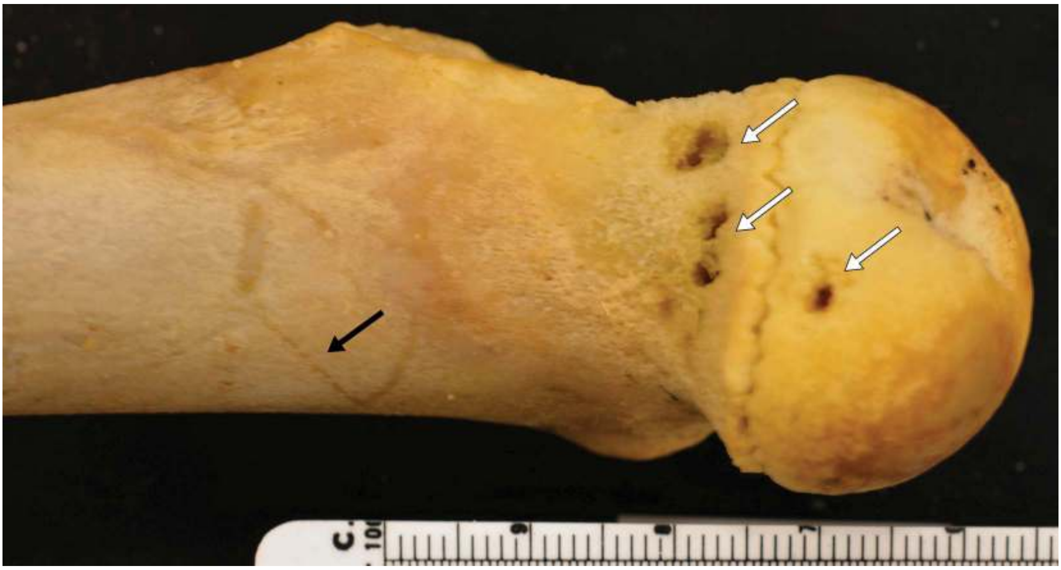

Figure 19.9 Multiple punctures (white arrows) on a pig (*Sus scrofa*) femoral head caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). Note hook scoring (black arrow) located distally of the femoral head. The scale is in cm.

carnivores is 3.0–13.0 mm, and mammals have not been noted to produce hook scores (Njau and Blumenschine 2006). The term *drag-snag* is used to describe similar tooth mark patterns to hook scores but which produce deep grooves/striae with an associated pit (Njau and Gilbert 2016). A drag-snag may appear as an elongated pit, with or without internal striations, and may appear with a pivot, creating a wide V-shaped mark with internal striations.

Punctures and Furrows

Punctures (Figures 19.9 and 19.10) are deeper depressions that penetrate through cortical bone. Punctures may have chipping on the margins and shallow to deep cracks propagating from opposite sides oriented parallel to the long axis of the bone. Punctures observed in crocodilians are sometimes bisected, similar to pits (Domínguez-Rodrigo and Piqueras 2003; Njau and Blumenschine 2006). Bisected punctures are generally not observed in mammalian carnivores. The average diameter of crocodilian punctures is 2.5–7.5 mm (Domínguez-Rodrigo and Piqueras 2003; Njau and Blumenschine 2006; Selvaggio and Wilder 2001). Sharp-blunt injuries visualized as depressed fractures with (sometimes) V-shaped pits are occasionally observed with puncture defects and are caused by the impact of the crocodile forcefully biting down on bone. If the bone does not collapse due to the force of the bite, a linear radiating fracture can be observed leading away from the impact location (Drumheller and Brochu 2014). Serial puncturing, observed occasionally in crocodilian feeding and similar to serial pits, occurs when crocodilians bite down on bone and multiple punctures are inflicted by adjacent teeth (Njau and Blumenschine 2006). Furrows (Figure 19.11) are linear patterns across the bone also with deep penetrations through cortical bone, but they are less often observed among crocodilian-created tooth marks than in mammalian carnivore tooth marks (Drumheller and Brochu 2014; Schneider 2018). Furrows are longer in length than width.

Figure 19.10 Serial punctures (black arrow) and a puncture (white arrow) on a pig (*Sus scrofa*) ilium caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). Serial tooth marks occur when crocodilians bite down on bone and adjacent teeth impact around surrounding area. The scale is in cm.

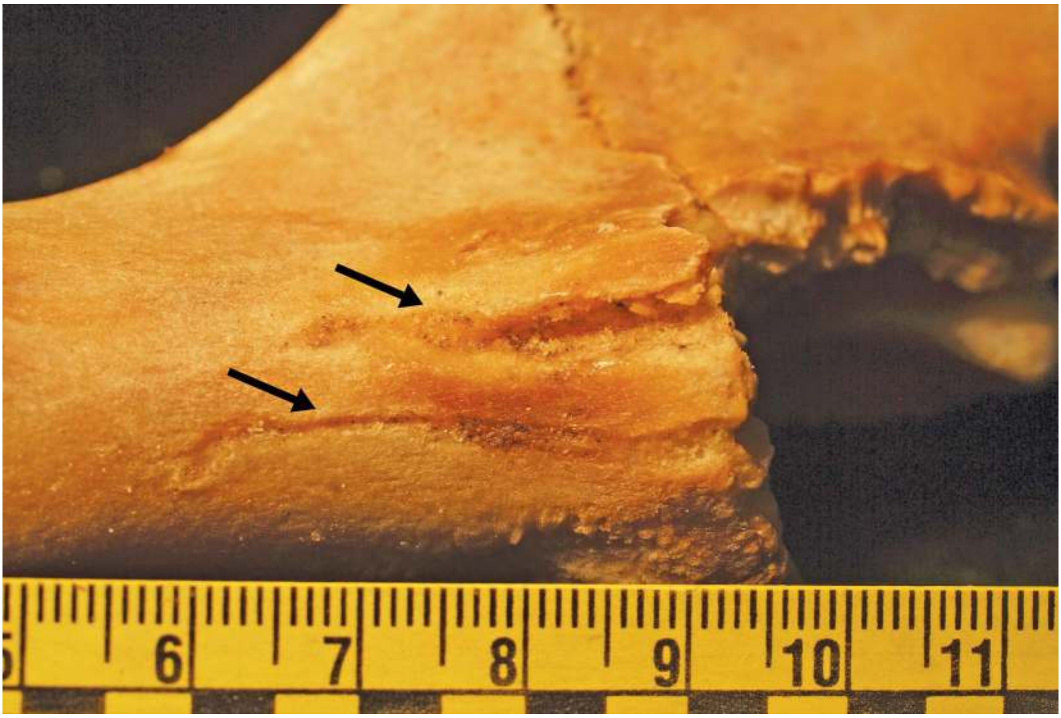

Figure 19.11 Furrows (arrows) on pig (*Sus scrofa*) pelvis near the acetabulum, caused by American alligator (*Alligator mississippiensis*) feeding (Schneider 2018). The scale is in cm.

Crocodilian Tooth Mark Patterns

Multiple researchers have examined crocodilian tooth mark patterns experimentally (Table 19.3). Drumheller and Brochu (2014) observed tooth marks of American alligators and compared the results to existing Nile and saltwater crocodile datasets to observe potentially diagnostic traits of bisected marks, hook scores, and a lack of furrows. Drumheller and Brochu (2014) fed groups of captive alligators partially butchered cow (*Bos taurus*) hind limbs and pig (*Sus scrofa*) femora. Scores were found to be the most common types of mark, representing 59.5% of all identified traces. Pits were the second most common marks, representing 31.4% of the recorded marks. Punctures comprised 8.4% of the remaining

Table 19.3 Summary of Crocodilian Tooth Mark Morphology Actualistic Studies

	Baquedano et al. (2012)	Drumheller and Brochu (2014)	Njau and Blumenschine (2006)	Schneider (2018)	Westaway et al. (2011)
Crocodilian (Consumer)	Crocodile (not specified; probable Nile crocodile [*Crocodylus niloticus*])	American alligator (*Alligator mississippiensis*)	Nile crocodile (*C. niloticus*)	American alligator (*A. mississippiensis*)	Saltwater crocodile (*C. porosus*)
Species Consumed	Pig and boar (*Sus scrofa*), sheep (*Ovis aries*), cow (*Bos taurus*)	Cow (*Bos taurus*), pig (*Sus scrofa*)	Goat (*Capra hircus*), cow (*Bos taurus*)	White-tailed deer (*Odocoileus virginianus*), pig (*Sus scrofa*)	Pig (*Sus scrofa*)
Total # of marks	n = 133	n = 4386	n = 2029	n = 412	n = 43
Pits	57	1205	Not recorded	189	Not noted
Scores	65	2282	Not recorded	136	16
Punctures	11	325	Not recorded	55	27
Hook Scores	Not noted	141	18	18	Not noted
Bisected Marks	33 of 57 pits and 24 of 65 scores were bisected	125 bisected pits; 227 bisected scores, 62 bisected punctures	205	10	Not noted
Furrows	Not noted	19	Not noted	4	Not noted
Percentage of Total Marks					
Pits	42.8%	31.4%	N/A	45.9%	N/A
Scores	48.8%	59.5%	N/A	33.0%	37.2%
Punctures	8.2%	8.4%	N/A	13.3%	62.8%
Hook Scores	N/A	6.1%	0.9%	4.4%	N/A
Bisected Marks	24.8% of all pits and 18.0% of all scores were bisected	10.3% of all pits, 9.9% of all scores, and 19.1% punctures were bisected	10.1%	2.4%	N/A
Fractures	Not noted	Observed	Not observed	Observed	Not noted
Furrows	Not noted	0.1%	Not observed	1.0%	Not noted

marks, and furrows represented only 0.1% of marks. Of these marks, 10.3% of all pits, 9.9% of all scores, and 19.1% of all punctures exhibited bisections, representing 10.8% of all recorded marks. At least one bisected mark was found on 83.6% of sampled bones. Bisected marks made by American alligators were found in rates similar to *C. niloticus*: 10.0% of all observed bite marks in *C. niloticus* and 10.8% in American alligators; 82.5% of individual marks on bones in *C. niloticus* and 83.6% in American alligators (Drumheller and Brochu 2014). Hook scores comprised 6.1% of all observed scores, were present on 62.5% of the observed bones, and were found at the highest rate in American alligators. Bone fracturing and furrowing created extensively by American alligators are notably rare or absent among *C. niloticus* and *C. porosus*. American alligators exhibited a more aggressive style of feeding, focusing more on crushing and fracturing prey (Drumheller and Brochu 2014). Size differences of individual crocodilians also may be a factor, as bones/limbs that are swallowed whole may require less crushing prior to swallowing.

Schneider (2018) utilized five adult and four young American alligators and tested a sample of pig and white-tailed deer (*Odocoileus virginianus*) bones to compare these taphonomic results to those caused by mammalian carnivores. A total of 412 tooth marks were observed on all 37 bones (Table 19.4): 189 pits (45.9%), 55 punctures (13.3%), 136 scores (33.0%), 4 furrows (1.0%), 18 hook scores (4.4%), and 10 bisected marks (2.4%). Edge polish, commonly observed in mammalian carnivore-altered samples, was not recorded, again indicating that this is a not a characteristic of crocodilians (Binford 1981; Njau and Blumenschine 2006; Chapter 9). The edges of all the proximal portions of the pelvis were crushed by the alligators.

Table 19.4 Tooth Marks on a Sample (n = 37) of Pig (*Sus scrofa*) and White-Tailed Deer (*Odocoileus virginianus*) Bones Caused by American Alligator (*Alligator mississippiensis*) Feeding

Tooth Mark	Bone portions	Femur (n=8)	Tibia (n=2)	Humerus (n=3)	Pelvis (n=2)	Ulna (n=11)	Radius (n=11)
Pits	Proximal	14	3	11	4	0	9
	Midshaft	86	0	41	0	7	0
	Distal	23	0	0	2	0	2
Punctures	Proximal	5	0	8	10	2	3
	Midshaft	0	0	0	0	0	0
	Distal	10	0	0	1	1	7
Scores	Proximal	1	5	0	7	16	0
	Midshaft	45	1	7	1	0	3
	Distal	6	1	3	2	3	26
Furrows	Proximal	0	0	0	1	0	0
	Midshaft	0	0	0	1	0	0
	Distal	2	0	0	0	0	0
Hook Scores	Proximal	0	1	0	0	0	0
	Midshaft	9	0	0	3	2	0
	Distal	1	0	0	0	0	1
Bisected marks	Proximal	0	1	0	0	0	0
	Midshaft	9	0	0	0	0	0
	Distal	0	0	0	0	0	0

Source: Schneider (2018).

Baquedano et al. (2012) observed tooth mark frequency and morphology on bone utilizing eight captive (zoo) female crocodiles, attempting to verify previous assessments of the degree of bone damage inflicted by crocodiles. The carcass portions included limbs from pig, boar, sheep, and cow. They identified tooth marks using similar criteria to Njau and Blumenschine (2006), dividing the marks into pits, punctures, and scores (including hook scores). A total of 133 tooth marks were observed: 57 pits, 65 scores, and 11 punctures. In addition, 33 bisected pits (24.8% of total tooth marks) and 24 bisected scores (18% of total tooth marks) were observed. Baquedano et al. (2012) found that their study supported previous research regarding the degree of damage inflicted by crocodiles while consuming carcasses. More than 80% of elements contained at least one diagnostic tooth mark created by a crocodilian.

Crocodilian feeding also can fracture bones. Njau and Blumenschine (2006) described fracture patterns and whole bone breakage, documenting spiral fractures which range from rare (Baquedano et al. 2012) to incomplete (Drumheller and Brochu 2014) from Nile crocodile feeding. Schneider (2018) also observed spiral fracture patterns among bones accessed by young American alligators. Though both the Nile crocodiles sampled by Njau and Blumenschine (2006) and the American alligators sampled by Drumheller and Brochu (2014) measured around 4 m in length, the American alligators caused more extensive damage, so variation by species may occur.

In an attempt to verify the patterns of modification described for Nile crocodiles and those of extinct crocodiles, Westaway et al. (2011) conducted a study with three captive saltwater crocodiles using two subadult pig carcasses. Each crocodile was allowed access to a carcass one at a time, and Westaway et al. (2011) observed that the crocodiles exhibited five of the six stages of crocodilian feeding behavior: capture, "kill", reduction, defleshing, and swallowing. Fracturing of the pig remains was frequent, especially on the axial skeleton; however, tooth marks on the remains were uncommon and only a few punctures and scores were observed in their sample. Tooth marks that were observed were isolated and mostly found on the skull, pelvis, and long bone epiphyses. Westaway et al. (2011) observed a total of 43 marks: 16 scores (37.2% of total tooth marks) and 27 punctures (62.8% of total tooth marks).

Delaney-Rivera et al. (2009) observed tooth marks on a varied sample of taxa and included comparative data from Domínguez-Rodrigo and Piqueras (2003), Selvaggio and Wilder (2001), and Pobiner (2007). Delaney-Rivera et al. (2009) presented 16 omnivores and carnivores (ranging from small to large in size) with defleshed goat fore- and hind-limbs and presented large carnivores with an additional defleshed cow femur. Their study suggested that only a limited number of inferences about taxa and body size could be made based upon the tooth pit dimensions and location. Different-sized taxa were found to create tooth mark dimensions that overlap in size. Specifically pertaining to crocodilians, Delaney-Rivera et al. (2009) observed bisected tooth pits on remains modified by an alligator, an example of diagnostic tooth mark morphology.

Focusing on patterns of shell breakage and behavior specific to chelonivory and not specifically on bite identification, Milàn et al. (2010) observed Dwarf caiman (*Paleosuchus palpebrosus*) bite modifications on red-eared slider (*Trachemys scripta*) shells. The caiman was observed manipulating the turtle into an upright position before applying jaw pressure, allowing the shell to be opened and emptied. This maneuver left several bite traces in the shells, including round punctures arranged in rows, elongated scores from teeth scraping along the shell, and large crushed areas from the repetitive bites applied to the same area.

Case Study: Nile Crocodile (*Crocodylus niloticus*) Scavenging in South Africa

In 2012, incomplete skeletal remains of a human juvenile were discovered in the town of Umkomaas, which is located in the KwaZulu-Natal province in South Africa. The primary attraction of the town is the Umkomazi River, which is the largest river on the South Coast of South Africa and is popular for both whale sightings and water sports. Rivers in South Africa are also home for the Nile crocodile, with crocodile attacks occurring to humans most often during the summer months (December to March) (Pooley 2019). The most frequent victims of crocodile attacks tend to be children who use rivers for swimming and bathing (Pooley 2019). The specific discovery location of the skeletal elements in Umkomaas was not known, and no photographs of the scene were made available to the forensic anthropologist. Interpretations were therefore limited to the analysis of the available bones. Only 12% (25 bones) of the entire skeleton was recovered, including the pelvis, lower limbs (femora and left tibia), and left foot (Figure 19.12). Using the KidStats program (Stull et al. 2014, 2017), data from the tibia and femur were used to estimate age at death (9–14 years) and sex (female) (Stull et al. 2014, 2017).

Random and densely packed tooth pits, striations, hook scores, and drag snags were noted on the pelvis, femora, left tibia, and left cuboid (Figures 19.13 and 19.14). In a forensic context, crocodilian predation/scavenging on bones can be easily confused with sharp-force trauma and/or dismemberment. Dismemberment is the action of removing body parts, such as head, limbs, hands, and feet, as a means to obscure personal identity, manage dispersal of a body, and sometimes due to a general loathing of the person (Symes et al. 2002). Perpetrators tend to focus on joints or make attempts to cut through entire bones with serrated knives and/or saws. While cutting through soft tissue with a knife, perpetrators tend to cut proximal and distal ends of a long bone, leaving distinct V-shaped patterns with potential striations from knife-cut wounds and kerfs from various classes of saws. The presence of these tool marks is often used to exclude terrestrial carnivore activity as a source of these defects. Scores, hook scores, and drag snags created from the anterior dentition of

Figure 19.12 Recovered skeletal elements from riverine areas of Umkomaas. Both femoral heads had been removed for DNA analysis by the South African Police Service (SAPS).

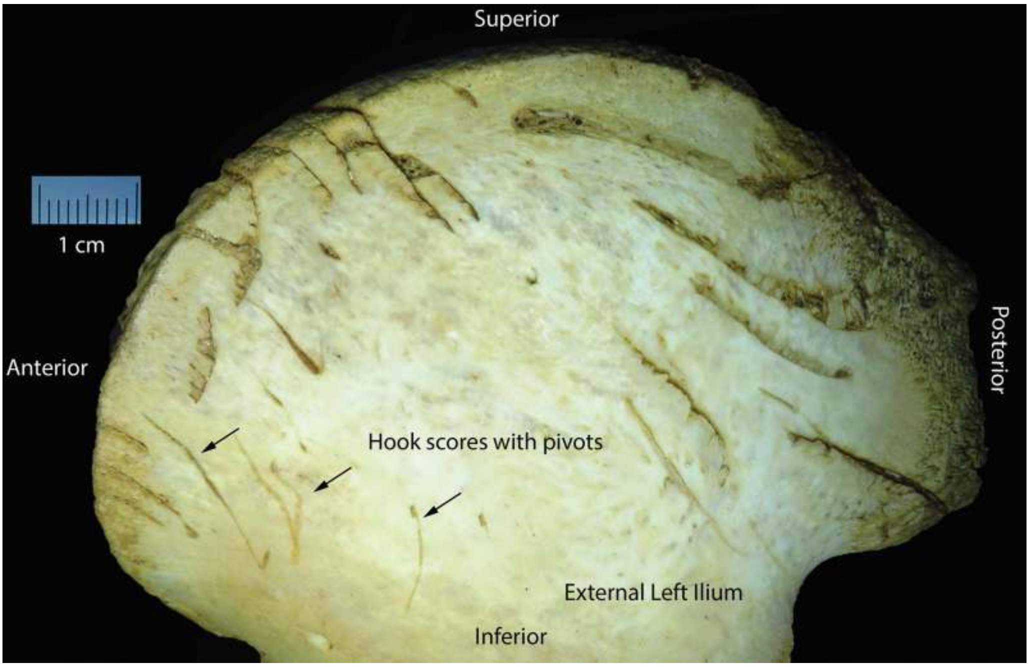

Figure 19.13 Random and dense distribution of hook scores and punctures on the external surface of the left ilium of the os coxa, consistent with Nile crocodile (*Crocodylus niloticus*). Three hook scores with pivots at a 45° angle (black arrow) are present. Based on the distribution of damage, the crocodile's grasp had gone across the hips and around the buttocks.

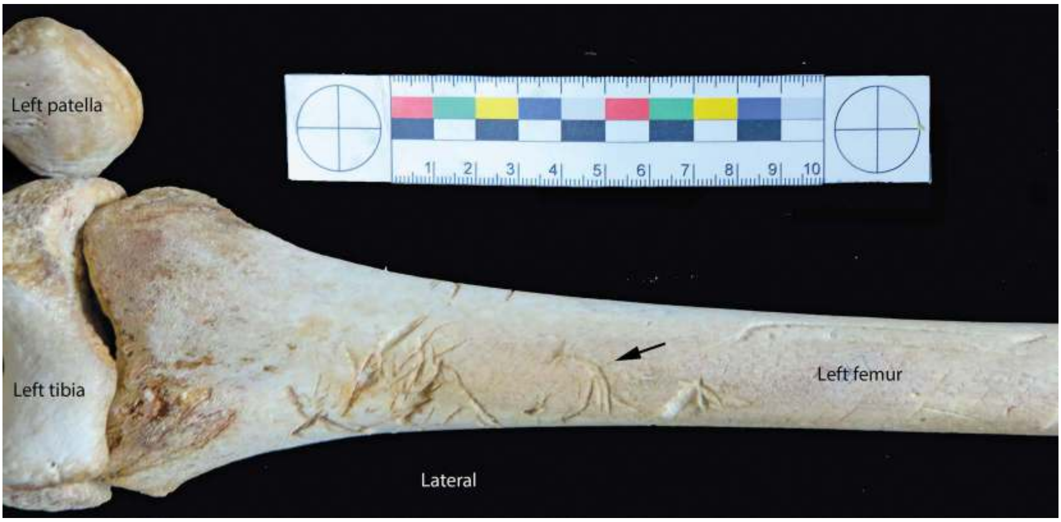

Figure 19.14 High density of tooth marks on the distal, lateral left femur, consistent with Nile crocodile (*Crocodylus niloticus*). Characteristics associated with crocodiles include: (1) intact distal and proximal end of long bones (tibia and femur), (2) a hook score at a 45° angle, and (3) cluster of tooth pits and drag-snags transversely orientated to the long axis of the bone.

crocodilians also present with V-shaped patterns and striations and also tend to cluster along the diaphysis and/or the proximal and distal ends of the bone (Figure 19.14).

Anthropologists tend to classify sharp trauma into categories with serrated and non-serrated knives; heavy chopping instruments such as machetes or swords; and various classes of saws, based on the profile, shape, and size of the kerf (e.g., Symes et al. 2002). For an injury to be associated with a sharp force, the wielding tool must have a beveled edge (Symes et al. 2002). A knife is simply defined as a blade with a cutting edge, and the edge must be beveled for it to be considered a tool that creates "knife cuts". Basically, incised wounds cannot be created unless the blade presents with an edged bevel. As mentioned above, the anterior teeth of crocodilians have carinae, or sharp ridges on the mesial and distal surface (Figure 19.3), which represent an edged bevel that contributes to the observable V-shaped defects with striations on the bone. The anterior teeth of extant terrestrial carnivores do not have these sharp, raised ridges of bone, and therefore these predators can only cause blunt force injuries along with punctures and pits on the bone. Three main differences between human-induced sharp force trauma and crocodilian activity are, for the latter: (1) increased density and randomness of defects on bone in a given area; (2) bisected pits and hook scores; and (3) an absence of dismemberment of the bone at the joints, with intact proximal and distal ends.

In this case, the distribution and density of punctures, hook scores, and drag snags are consistent with Nile crocodile predation/scavenging (Figures 19.13–19.17). At least 140 defects were observed on seven skeletal elements, namely the right ilium (n = 14), left ilium (n = 23), left ischium (n = 2), left femur (n = 42), right femur (n = 39), left tibia (n = 18), and left cuboid (n = 2). The left hip (left ilium, Figure 19.13) and left leg (femur) had the greatest number of defects, namely pits, hook scores, and drag snags, on the superior iliac blade and around the anterior superior iliac spine, whereas in the lower limbs the presence of similar

Figure 19.15 Close-up view of distal left femur, lateral, with several pseudo-cuts in bone with and without snags are observed (blue arrow), consistent with Nile crocodile (*Crocodylus niloticus*). A drag snag with striations is indicated with the black arrow.

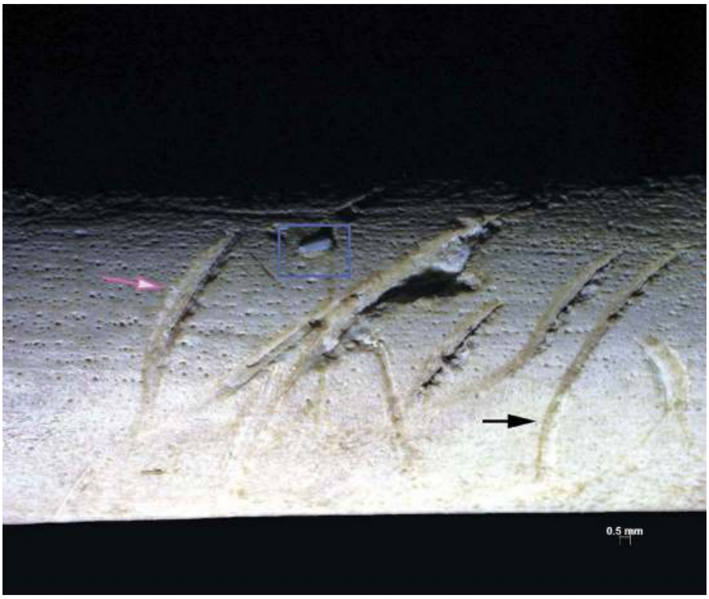

Figure 19.16 Close-up view of the midshaft of the left tibia, showing pseudo-cuts without snags, (pink arrow), as well as hook scores (black arrow), consistent with Nile crocodile (*Crocodylus niloticus*). A bisected puncture mark (blue box) has an embedded, carinated crocodilian tooth fragment.

defects tended to cluster around the diaphyseal shafts of the long bones. Consistent with the literature on crocodilian predation/scavenging, none of these defects resulted in the complete separation of a bone, or bones, from each other (Baquedano et al. 2012; Njau and Blumenschine 2006; Njau and Gilbert 2016). Only one puncture was noted on the articular surface of a bone (distal left femur), and no other defects were noted around the hip, knee or ankle joints. The left tibia also retained the broken-off tip of a carinated tooth (Figures 19.16 and 19.17), which was clear evidence of crocodile involvement.

Other Reptiles

Multiple species of monitor lizards, genus *Varanus*, live throughout Africa, southern Asia, and Oceania, and these have received some study regarding their ability to modify bones. Komodo monitors (“dragons”; *Varanus komodoensis*) are native to Indonesia and are the largest extant lizard species. D’Amore and Blumenschine (2009, 2012) examined the traces of feeding behavior of captive (zoo) monitor lizards on multiple goat (*Capra hircus*) carcasses in order to determine the characteristics of marks produced by ziphodont (“sword tooth”; labio-lingually compressed, distally curved, and serrated) teeth. The most common marks by far were scores, with fewer pits and “edge marks” along the thin margins of bones, and rare punctures and furrows; some marks also included separate striations from the tooth serrations. Most marks were narrow (<1 mm) but varied in length. Komodo monitors are known to prey upon large mammal species, including humans (Hart and Sussman 2008:124–127). Smaller lizard species likely lack significant bone modification behavior or ability, but further taphonomic experimentation is required to test this assumption.

Figure 19.17 Jagged scores on the anterior midshaft of the left tibia, which are consistent with Nile crocodile (*Crocodylus niloticus*). A bisected puncture mark (white box) has an embedded, carinated crocodilian tooth fragment.

Other reptile species have not been examined in detail for their bone modification behavior; in particular, two species of turtle (Order Testudines) that are common in the USA, snapping turtle (*Chelydra serpentina*) and alligator snapping turtle (*Macrochelys temminckii*) and their relatives in the family Chelydridae in Central and South America. Snapping turtles are found throughout the eastern two-thirds of the USA and into southern Canada and northeast Mexico and have a broad, omnivorous diet that includes invertebrates, vertebrates, and scavenging; adults ambush hunt small prey (Spotila and Bell 2008). Alligator snapping turtles are confined to southern climates centering on the Mississippi basin, from Texas to Florida (Ernst 2008) and have a similarly broad diet that also includes at least some scavenging (East and Ligon 2013). Both species are therefore possible scavengers of human remains in wetlands and adjacent terrestrial environments, and direct observational studies of wild turtles with bait carcasses are necessary to assess their potential impacts upon soft tissue, markings upon bone, and dispersal.

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References

Alderton, D. (1991) *Crocodiles and Alligators of the World*. Facts on File, New York.

Aramendi, J., M. A. Maté-González, J. Yravedra, M. Cruz Ortega, M. Carmen Arriaza, D. González-Aguilera, E. Baquedano, and M. Domínguez-Rodrigo (2017) Discerning carnivore agency through the three-dimensional study of tooth pits: Revisiting crocodile feeding behaviour at FLK- Zinj and FLK NN3 (Olduvai Gorge, Tanzania). *Palaeogeography, Palaeoclimatology, Palaeoecology* 488:93–102.

Baquedano, E., M. Domínguez-Rodrigo, and C. Musiba (2012) An experimental study of large mammal bone modification by crocodiles and its bearing on the interpretation of crocodile predation at FLK Zinj and FLK NN3. *Journal of Archaeological Science* 39(6):1728–1737.

Biknevicius, A. R., and C. B. Ruff (1992) The structure of the mandibular corpus and its relationship to feeding behavior in extant carnivores. *Journal of Zoology, London* 228(3):479–507.

Binford, L. R. (1981) *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Botfalvai, G., E. Prondvai, and A. Ősi (2014) Inferred bite marks on a Late Cretaceous (Santonian) bothremydid turtle and a hylaeochampsid crocodilian from Hungary. *Cretaceous Research* 50:304–317.

Boyd, C. A., S. K. Drumheller, and T. A. Gates (2013) Crocodyliform feeding traces on juvenile ornithischian dinosaurs from the Upper Cretaceous (Campanian) Kaiparowits Formation, Utah. *PLoS ONE* 8:e57605. DOI: 10.1371/journal.pone.0057605.

Britton, A. (2012) Crocodilian Species List. Electronic document, http://crocodilian.com/cnhc/csl.html, accessed 20 October 2020.

Brochu, C. A., J. Njau, R. J. Blumenschine, and L. D. Densmore (2010) A new horned crocodile from the Plio-Pleistocene hominid sites at Olduvai Gorge, Tanzania. *PLoS ONE* 5(2):e9333. DOI: 10.1371/journal.pone.0009333.

Caldicott, D. G. E., D. Croser, C. Manolis, G. Webb, and A. Britton (2005) Crocodile attack in Australia: An analysis of its incidence and review of the pathology and management of crocodilian attacks in general. *Wildlife and Environmental Medicine* 16:143–159.

Chattopadhyay, S., B. Shee, and B. Sukul (2013) Fatal crocodile attack. *Journal of Forensic and Legal Medicine* 20(8):1139–1141.

Cleuren, J., and F. De Vree (2000) Feeding in crocodilians. In *Feeding: Form, Function, and Evolution in Tetrapod Vertebrates* ed. by K. Schwenk, pp. 337–358. Academic Press, San Diego, CA.

Conover, M. R. (2019) Numbers of human fatalities, injuries, and illnesses in the United States due to wildlife. *Human-Wildlife Interactions* 13(2):264–276.

D'Amore, D. C., and R. J. Blumenschine (2009) Komodo monitor (*Varanus komodoensis*) feeding behavior and dental function reflected through tooth marks on bone surfaces, and the application to ziphodont paleobiology. *Paleobiology* 35(4):525–552.

D'Amore, D. C., and R. J. Blumenschine (2012) Using striated tooth marks on bone to predict body size in theropod dinosaurs: A model based on feeding observations of *Varanus komodoensis*, the Komodo monitor. *Paleobiology* 38(1):79–100.

D'Amore, D. C., M. Harmon, S. K. Drumheller, and J. J. Testin (2019) Quantitative heterodonty in Crocodylia: Assessing size and shape across modern and extinct taxa. *PeerJ* 7:e6485. DOI: 10.7717/peerj.6485.

Davidson, I., and S. Solomon (1990) Was OH7 the victim of a crocodile attack? In *Problem Solving in Taphonomy: Archaeological and Palaeontological Studies from Europe, Africa and Oceania* ed. by S. Solomon, I. Davidson, and D. Watson, pp. 197–206. Tempus, St. Lucia, Qld, Australia.

Delaney-Rivera, C., T. W. Plummer, J. A. Hodgson, F. Forrest, F. Hertel, and J. S. Oliver (2009) Pits and pitfalls: Taxonomic variability and patterning in tooth mark dimensions. *Journal of Archaeological Science* 36(11):2597–2608.

Diefenbach, C. O. da C. (1975a) Gastric function in *Caiman crocodylus* (Crocodylia: Reptilia)—I. Rate of gastric digestion and gastric motility as a function of temperature. *Comparative Biochemistry and Physiology* 51A:259–265.

Diefenbach, C. O. da C. (1975b) Gastric function in *Caiman crocodylus* (Crocodylia: Reptilia)—II. Effects of temperature on pH and proteolysis. *Comparative Biochemistry and Physiology* 51A:267–274.

Domínguez-Rodrigo, M. and A. Piqueras (2003) The use of tooth pits to identify carnivore taxa in tooth-marked archaeofaunas and their relevance to reconstruct hominid carcass processing behaviours. *Journal of Archaeological Science* 30(11):1385–1391.

Drumheller, S. K., and C. A. Brochu (2014) A diagnosis of *Alligator mississippiensis* bite marks with comparisons to existing crocodylian datasets. *Ichnos* 21(2):131–146.

East, M. B., and D. B. Ligon (2013) Comparison of diet among reintroduced and wild juvenile alligator snapping turtles (*Macrochelys temminckii*) and adult female Ouachita map turtles (*Graptemys ouachitensis*). *The Southwestern Naturalist* 58(4):450–458.

Enax, J., H.-O. Fabritius, A. Rack, O. Prymak, D. Raabe, and M. Epple (2013) Characterization of crocodile teeth: Correlation of composition, microstructure, and hardness. *Journal of Structural Biology* 184(2):155–163.

Erickson, G. M., P. M. Gignac, S. J. Steppan, A. K. Lappin, K. A. Vliet, J. D. Brueggen, B. D. Inouye, D. Kledzik, and G. J. W. Webb (2012) Insights into the ecology and evolutionary success of crocodilians revealed through bite-force and tooth-pressure experimentation. *PLoS ONE* 7(3):e31781. DOI: 10.1371/journal.pone.0031781.

Erickson, G. M., A. K. Lappin, T. Parker, and K. A. Vliet (2004) Comparison of bite-force performance between long-term captive and wild American alligators. *Journal of Zoology, London* 262:21–28.

Ernst, C. H. (2008) Systematics, taxonomy, and geographic distribution of the snapping turtles, family Chelydridae. In *Biology of the Snapping Turtle* (Chelydra serpentina), ed. by A. C. Steyermark, M. S. Finkler, and R. J Brooks, pp. 71–79. Johns Hopkins University Press, Baltimore.

Fish, F. E., S. A. Bostic, A. J. Nicastro, and J. T. Beneski (2007) Death roll of the alligator: Mechanics of twist feeding in water. *Journal of Experimental Biology* 210(16):2811–2818.

Fisher, D. C. (1981a) Crocodilian scatology, microvertebrate concentrations, and enamel-less teeth. *Paleobiology* 7(2):262–275.

Fisher, D. C. (1981b) Mode of preservation of the Shotgun Local Fauna (Paleocene, Wyoming) and its implication for the taphonomy of a microvertebrate concentration. *Contributions from the Museum of Paleontology, the University of Michigan* 25(12):247–257.

Fisher, D. C. (1981c) Taphonomic interpretation of enamel-less teeth in the Shotgun Local Fauna (Paleocene, Wyoming). *Contributions from the Museum of Paleontology, the University of Michigan* 25(13):259–275.

Florida Fish and Wildlife Conservation Commission (2019a) Florida Fish and Wildlife Conservation Commission Alligator Bites on People in Florida. Electronic document, https://myfwc.com/media/1716/alligator-gatorbites.pdf, accessed 30 October 2020.

Florida Fish and Wildlife Conservation Commission (2019b) Human-Alligator Incidents Fact Sheet. Electronic document, https://myfwc.com/media/1776/human-alligatorincidentfactsheet.pdf, accessed 30 October 2020.

Fukuda, Y., C. Manolis, and K. Appel (2014) Management of human-crocodile conflict in the Northern Territory, Australia: Review of crocodile attacks and removal of problem crocodiles. *The Journal of Wildlife Management* 78(7):1239–1249.

Fukuda, Y., C. Manolis, K. Saalfeld, and A. Zuur (2015) Dead or alive? Factors affecting the survival of victims during attacks by saltwater crocodiles (*Crocodylus porosus*) in Australia. *PLoS ONE* 10(5):e0126778. DOI: 10.1371/journal.pone.0126778.

Grigg, G., and D. Kirshner (2015) *Biology and Evolution of Crocodylians*. Cornell University Press, Ithaca, NY.

Gruen, R. L. (2009) Crocodile attacks in Australia: Challenges for injury prevention and trauma care. *World Journal of Surgery* 33(8):1554–1561.

Haddad, V., Jr., and W. C. Fonseca (2011) A fatal attack on a child by a black caiman (*Melanosuchus niger*). *Wilderness and Environmental Medicine* 22(1):62–64.

Harding, B. E., and B. C. Wolf (2006) Alligator attacks in southwest Florida. *Journal of Forensic Sciences* 51(3):674–677.

Hart, D. L., and R. W. Sussman (2008) *Man the Hunted: Primates, Predators, and Human Evolution* (rev. ed.). Westview Press, Cambridge, MA.

Hertner, G. (2006) Caiman bite. *Wilderness and Environmental Medicine* 17:267–270.

Joyce, W. G. (2000) The first complete skeleton of *Solnhofia parsonsi* (Cryptodira, Eurysternidae) from the Upper Jurassic of Germany and its taxonomic implications. *Journal of Paleontology* 74(4):684–700.

Langley, R. L. (2005) Alligator attacks on humans in the United States. *Wilderness and Environmental Medicine* 16(3):119–124.

Langley, R. L. (2010) Adverse encounters with alligators in the United States: An update. *Wilderness & Environmental Medicine* 21(2):156–163.

Mekisic, A. P., and J. R. Wardill (1992) Crocodile attacks in the Northern Territory of Australia. *Medical Journal of Australia* 157(11–12):751–754.

Meyer, C. A. (1994). Depositional environment and paleoecology of the Solothurn Turtle limestone (Kimmeridgian, Northern Switzerland). *Geobios* 27(S1):227–236.

Mikuláš, R., E. Kadlecová, O. Fejfar, and Z. Dvořák (2006) Three new ichnogenera of biting and gnawing traces on reptilian and mammalian bones: A case study from the Miocene of the Czech Republic. *Ichnos* 13(3):133–127.

Milàn, J., J. Kofoed, and R. G. Bromley (2010) Crocodylian-chelonian carnivory: Bite traces of dwarf caiman, *Paleosuchus palpebrosus*, in red-eared slider, *Trachemys scripta*, carapaces. *New Mexico Museum of Natural History and Science, Bulletin* 51:195–200.

National Park Service (2017) American alligator species profile. Electronic document, https://www.nps.gov/ever/learn/nature/alligator.htm, accessed 17 October 2020.

Njau, J. K, and R. J. Blumenschine (2006) A diagnosis of crocodile feeding traces on larger mammal bone, with fossil examples from the Plio-Pleistocene Olduvai Basin, Tanzania. *Journal of Human Evolution* 50(2):142–162.

Njau, J. K., and R. J. Blumenschine (2012) Crocodylian and mammalian carnivore feeding traces on hominid fossils from FLK 22 and FLK NN 3, Plio-Pleistocene, Olduvai Gorge, Tanzania. *Journal of Human Evolution* 63(2):408–417.

Njau, J., and H. Gilbert (2016) Standardizing terms for crocodile-induced bite marks on bone surfaces in light of the frequent bone modification equifinality found to result from crocodile feeding behavior, stone tool modification, and trampling. *FOROST Occasional Publications* 3:1–13.

Noto, C., D. J. Main, and S. K. Drumheller (2012) Feeding traces and paleobiology of a Cretaceous (Cenomanian) crocodyliform: Example from the Woodbine Formation of Texas. *Palaios* 27(2):105–115.

Pobiner, B. L. (2007) *Hominin-Carnivore Interactions: Evidence from Modern Carnivore Bone Modification and Early Pleistocene Archaeofaunas (Koobi Fora, Kenya; Olduvai Gorge, Tanzania)*. Ph.D. Dissertation, Rutgers University, Newark, NJ.

Pobiner, B. (2008) Paleoecological information from predator tooth marks. *Journal of Taphonomy* 6(3-4):373–397.

Poole, D. G. (1961) Notes on tooth replacement in the Nile crocodile. *Proceedings of the Zoological Society of London* 136(1):131–140.

Pooley, S. (2015) Using predator attack data to save lives, human and crocodilian. *Oryx* 49(4): 581–583.

Pooley, S. (2016) The entangled relations of humans and Nile crocodiles in Africa, c. 1840–1992. *Environment and History* 33(2):421–454.

Pooley, S. (2019) When and where do Niles crocodiles attack? Here is what we found. The Conversation. Electronic document, https://theconversation.com/when-and-where-do-nile-crocodiles-attack-heres-what-we-found-119037, accessed 3 March 2021.

Pooley, A. C., T. Hines, and J. Shield (1992) Attacks on humans. In *Crocodiles and Alligators* (2nd ed.) ed. by C.A. Ross, pp. 172–187. Blitz Editions, London.

Rivera-Sylva, H. E., E. Frey, and J. R. Guzmán-Gutiérrez (2009) Evidence of predation on the vertebra of a hadrosaurid dinosaur from the Upper Cretaceous (Campanian) of Coahuila, Mexico. *Carnets de Geologie* CG2009(L02):1–6.

Saalfeld, D. T. (2010) *American Alligator* (Alligator mississippiensis) *Ecology in Inland Wetlands of East Texas*. Ph.D. Dissertation, Austin State University, Austin, TX.

Sahle, Y., S. El Zaatari, and T. D. White (2017) Hominid butchers and biting crocodiles in the African Plio-Pleistocene. *Proceedings of the National Academy of Sciences of the United States of America* 114(50):13164–13169.

Sala, N., and J. L. Arsuaga (2013) Taphonomic studies with wild brown bears (*Ursus arctos*) in the mountains of northern Spain. *Journal of Archaeological Science* 40(2):1389–1396.

Sala, N., J. L. Arsuaga, and G. Haynes (2014) Taphonomic comparison of bone modifications caused by wild and captive wolves (*Canis lupus*). *Quaternary International* 330(1):126–135.

Schneider, C. S. (2018) *Alligator* (Alligator mississippiensis) *Taphonomy: Analysis of Gnawed and Digested Bone*. M.S. Thesis, Boston University School of Medicine, Boston.

Selvaggio, M. M. and J. Wilder (2001) Identifying the involvement of multiple carnivore taxa with archaeological bone assemblages. *Journal of Archaeological Science* 28(5):465–470.

Shepherd, S. M., and W. H. Shoff (2014) An urban Northeastern United States alligator bite. *American Journal of Emergency Medicine* 32(5):487.e1–487.e3.

Sinton, T. J., and R. W. Byard (2016) Pathological features of fatal crocodile attacks in northern Australia, 2005-2014. *Journal of Forensic Sciences* 61(6):1553–1555.

Somma, L. A. (2021) *Alligator mississippiensis* Daudin, 1802: U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL. Electronic document, https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=221. Revision date 13 June 2019, accessed 3 January 2021.

Somma, L. A., and P. Fuller (2021) *Caiman crocodilus* Linnaeus, 1758: U.S. Geological Survey, Nonindigenous Aquatic Species Database, Gainesville, FL. Electronic document, https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=222. Revision date 22 June 2012, accessed 3 January 2021.

Spotila, J. R., and B. A. Bell (2008) Thermal ecology and feeding of the snapping turtle, *Chelydra serpentina*. In *Biology of the Snapping Turtle* (Chelydra serpentina), ed. by A. C. Steyermark, M. S. Finkler, and R. J Brooks, pp. 71–79. Johns Hopkins University Press, Baltimore.

Stull, K. E., E. N. L'Abbé, and S. D. Ousley (2014) Application of multivariate adaptive regression splines to estimate subadult age-at-death from diaphyseal dimensions. *American Journal of Physical Anthropology* 154(3):376–386.

Stull, K. E., E. N. L'Abbé, and S. D. Ousley (2017) Subadult sex estimation from diaphyseal dimensions in subadults up to 12 years old. *American Journal of Physical Anthropology* 63(1):64–74.

Symes, S. A., J. A. Williams, E. A. Murray, J. M. Hoffman, T. D. Holland, J. M. Saul, F. P. Saul, and E. J. Pope (2002) Taphonomic context of sharp-force trauma in suspected cases of human mutilation and dismemberment. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 403–434. CRC Press, Boca Raton, FL.

US Fish and Wildlife Service (2021) American crocodile *Crocodylus acutus*; Multi-species recovery plan for south Florida. Electronic document, https://www.fws.gov/verobeach/MSRPPDFs/Croc.pdf, accessed 3 January 2021.

Wallace, K. M., and A. J. Leslie (2008) Diet of the Nile crocodile (*Crocodylus niloticus*) in the Okavango Delta, Botswana. *Journal of Herpetology* 42(2):361–368.

Westaway, M. C., J. C. Thompson, W. B. Wood, and J. Njau (2011) Crocodile ecology and the taphonomy of early Australasian sites. *Environmental Archaeology* 16(2):124–136.

Wolf, B. C., and B. E. Harding (2014) Fatalities due to exotic and indigenous species in Florida. *Journal of Forensic Sciences* 59(1):155–160.

Wood, W. B. (2008) Forensic identification in fatal crocodile attacks. In *Forensic Approaches to Death, Disaster and Abuse* ed. by M. Oxenham, pp. 243–260. Australian Academic Press, Bowen Hills, Qld, Australia.

Woodward, A. R., E. H. Leone, H. J. Dutton, J. E. Waller, and L. Hord (2019) Characteristics of American alligator bites on people in Florida. *The Journal of Wildlife Management* 83(6):1437–1453.

Laws of Taphonomic Relative Timing

20

JAMES T. POKINES

Contents

> It is very customary for pawnbrokers in England, when they take a watch, to scratch the numbers of the ticket with a pin-point upon the inside of the case. It is more handy than a label as there is no risk of the number being lost or transposed. There are no less than four such numbers visible to my lens on the inside of this case. Inference—that your brother was often at low water. Secondary inference—that he had occasional bursts of prosperity, or he could not have redeemed the pledge. Finally, I ask you to look at the inner plate, which contains the keyhole. Look at the thousands of scratches all round the hole—marks where the key has slipped. What sober man's key could have scored those grooves? But you will never see a drunkard's watch without them. He winds it at night, and he leaves these traces of his unsteady hand. Where is the mystery in all this?
>
> **—Sir Arthur Conan Doyle**
> *The Sign of Four*

Introduction

As other chapters of this volume have illustrated, the taphonomic effects accrued on bones often indicate the environment or environments in which they resided during the postmortem interval (PMI); whether this was burial in soil (Chapter 5); immersion in a river (Chapter 6) or ocean (Chapter 7); deposition on the terrestrial surface, where the processes of decomposition (Chapter 3), scavenging (Chapters 9, 16, 18, and 19), subaerial weathering and other staining effects (Chapters 11 and 12) accrue; or artificial environments such as a coffin burial (Chapter 5) or indoors though use in anatomical teaching, ritual, or trophy display (Chapter 8). This determination can be important for remains that are from an unclear context, especially where these have been in long-term storage

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awaiting proper analysis and provenience information is incomplete (Pokines 2018). Reduction of these backlogs has been aided greatly by identification resources, such as database of unknown cases managed by the National Missing and Unidentified Persons System (NamUs 2021) and the DNA analysis provided by University of North Texas Center for Human Identification (UNTCHI 2021). As discussed below, some remains travel through multiple environments and accrue multiple taphonomic effects from these different episodes during the PMI. The relative timing of both the taphonomic effects accrued while in one depositional environment or successively between multiple environments often can be determined, in much the same manner and following similar laws as those for archaeological or geological stratigraphic analysis (Harris 1975, 1977, 1979, 1989; Pokines 2021). While various taphonomic agencies damage bone and remove portions needed to determine the biological profile, they also add information about the taphonomic history of the bone (Behrensmeyer and Kidwell 1985; Binford 1981; Ubelaker 1997; Chapter 1).

Just as a full taphonomic accounting should be a standard part of any skeletal analysis/report (Dirkmaat and Cabo 2016; Haglund and Sorg 1997; Pokines 2018; SWGANTH 2013; Chapter 1), including bench notes (Chapter 21), data and interpretations regarding the relative timing of taphonomic effects should be included. This additional aspect is especially important where possible perimortem trauma is present (Ubelaker and Adams 1995; Wheatley 2008; Wieberg and Wescott 2008; Chapter 13), and there is a need to establish the postmortem chain of events in sequence in order to substantiate that conclusion. In these cases, the characteristics of the fractures themselves can aid in determining if they are more typical of wet or dry bone. These data are used in combination with any other evidence that a given break or mark upon bone formed during either the perimortem or postmortem interval. If other taphonomic effects must have been formed after the death of the individual, and these occurred before the suspected trauma, then the break/mark could not be attributed to the death event.

Other taphonomic processes, especially dispersal through scavenger or water action (Chapters 6, 7, 9, 16, and 19), are of importance, since they increase the size of recovery scenes; these processes therefore impact heavily on the amount of effort and methods needed in scene processing (Chapter 17). As the radius of dispersal increases linearly, the area of the site potentially to be searched increases as a square function, so doubling the distance of dispersal quadruples the amount of scene processing. Along these same lines, studies of dispersal distances by various species have not been explored as much as is necessary to plan forensic recoveries. Much dispersal research has involved paleontologists researching modern scavengers in order to understand site deposition patterns of hominin sites (Behrensmeyer 2008; Behrensmeyer et al. 2003; Berger 2006; Berger and McGraw 2007; Davidson and Solomon 1990; Njau and Blumenschine 2012; Pante et al. 2012; Pickering et al. 2004; Pobiner 2007). Much of this research overlaps in relevance to forensic researchers, who need to know how far bones typically are moved in the environments within their jurisdiction and the behavior of the extant dispersing species (Young et al. 2014, 2015). The relative timing of postmortem disarticulation is relevant to both forensic and paleontological taphonomy, to understand overall skeletal recovery patterns, body transportation, and dispersal distances (Haglund 1993, 1997; Haglund et al. 1989; Haglund and Sorg 2002; Haynes 1980; Hill and Behrensmeyer 1984).

Forensic taphonomy also differs in its goals from paleontological taphonomy in its emphasis upon the individual instead of the entire assemblage and its depositional history, formation biases, and time averaging (Behrensmeyer 1991; Behrensmeyer and Kidwell 1985; Donovan 1991; Efremov 1940; Lyman 1994; Martin 1999; Weigelt 1989 [1927]). Less paleontological research therefore has been devoted to the questions of the timing of individual effects to bones and more upon the total set of changes. Some of the taphonomic effects examined below, such as some kinds of staining to bone, are unlikely to survive fossilization, so their formation over the forensic PMI is not of research interest to paleontologists.

An examination of the relative timing of taphonomic effects also is necessary to reconstruct the postmortem history of a forensic scene, which can follow typical patterns in some environments. A common sequence in terrestrial scenes is large carnivore scavenging, followed by environmental effects of subaerial weathering, algae formation, and soil staining, then rodent dry-bone gnawing, with gradual dispersal of remains from their point of initial deposition occurring throughout. Separation of natural from human-caused effects to skeletal remains is also one of the primary goals of forensic taphonomy, and this distinction can be aided by the analysis of the relative timing of the effects. Some instances of unusually good preservation where the remains of an individual hominin specimen can be associated do occur in paleontology and may allow some examination of the circumstances around death (Behrensmeyer 2008; Behrensmeyer et al. 2003; Behrensmeyer and Reed 2013; Berger 2006; Berger and McGraw 2007; Churchill et al. 2009; Davidson and Solomon 1990; L'Abbé et al. 2015; Njau and Blumenschine 2012). Paleontologists also are concerned with broad patterns of bone damage and their relative timing in analyses of carcass access and which taxon, hominins or competing vertebrate scavengers, had first access to the food resource and if active hunting was involved (Domínguez-Rodrigo 2002; Pante et al. 2012; Pickering et al. 2004).

Precedents for Laws of Relative Timing in the Natural Sciences

Geological science was the first to produce laws of relative timing, which were necessary to understand the sequences of bedrock laid down and how they formed. Their codification dates at least to the 17th century, including the work of Nicolas Steno (Oldenburg 1671; Steno 1669). Steno reasoned that encased bodies in rock (i.e., fossils) must have existed prior to their surrounding matrix, which must have been fluid when formed. Fossils therefore preceded their sedimentary matrix. He also makes first notice of the law of superposition, reasoning that lower beds must have formed prior to the ones above them, rock beds that are similar in form must have been formed in a similar manner, and sedimentary rock beds that were no longer horizontal must have started out flat and later gotten shifted. Hutton (1788) published many geological observations, including on the uniformitarianism principle, whereby the processes shaping the modern Earth were in operation in the same manner in the past. Smith (1816) applied the law of superposition to create the first geological map of England. He also provided further basis for the law of strata, indicating that these can be identified by their unique fossil assemblages even where a discontinuity has separated portions of the same formation. Lyell (1830–1833) codified many geological principles, including additional observations on the uniformitarianism principle, and referred specifically to "laws of superposition" in relative dating of rock formations. Other relevant laws include the law of faunal succession, where the known evolutionary history of a taxon or taxa can be used for relative (and absolute) dating (Harris 1989).

Many of these same general principles have been applied to archaeology, although the formation processes are different from those for sedimentary rock. By the 1700s, antiquarians like Stukeley in England already were applying principles of superposition, inclusions, and cross-cutting to supply relative dating to pre-Roman sites (Trigger 1989). Harris (1975, 1977, 1979, 1989) in particular codified laws of relative dating for archaeological analysis. These form the basis for the taphonomic laws discussed here along with observations of forensic cases in multiple depositional environments (Pokines 2021).

The Law of Superposition (Harris 1989:30): *In a series of layers and interfacial features, as originally created, the upper limits of stratification are younger and the lower are older, for each must have been deposited on, or created by the removal of, a pre-existing mass of archaeological stratification.* Superposition also includes intrusive features, i.e., those that were formed by cutting into a previous layer, which is common among both geological (in the case of igneous veins cutting through previous stratigraphy) and archaeological stratigraphy.

The Law of Original Horizontality (Harris 1989:31): *Any archaeological layer deposited in an unconsolidated form will tend towards a horizontal position. Strata which are found with tilted surfaces were originally deposited that way, or lie in conformity with the contours of a pre-existing basin of deposition.* This law derives more directly from geology, in that sedimentary layers are typically laid down in horizontal bands. As discussed below, horizontality is not as relevant to the taphonomic effects upon bones, many of which can accrue from directions that have nothing to do with gravity. Some effects, however, do accrue relative to a specific bone position or orientation.

The Law of Original Continuity (Harris 1989:32): *Any archaeological deposit, as originally laid down, or any interfacial feature, as originally created, will be bounded by a basin of deposition, or may thin down to a feather-edge. Therefore, if any edge of a deposit or interfacial feature is exposed in a vertical view, a part of its original extent must have been removed by excavation or erosion, and its continuity must be sought, or its absence explained.* This law also derives from geology but applies to archaeological strata as well: the abrupt termination of a layer is due to the removal of a portion, or they otherwise would be expected to taper away (i.e., a lens). As discussed below, some taphonomic effects can be expected not to have an abrupt termination point, so such extremities may be due to the later removal of a portion of the area of the earlier taphonomic effect.

The Law of Stratigraphical Succession (Harris 1989:34): *A unit of archaeological stratification takes its place in the stratigraphic sequence of a site from its position between the undermost (or earliest) of the units which lie above it and the uppermost (or latest) of all the units which lie below it and with which the unit has a physical contact, all other superpositional relationships being redundant.* A series of strata or other archaeological deposits can be related to the ones immediately before or after them, and the entire stratigraphic sequence of a site is derived from these individual sets of linkages. These principles also apply to taphonomic effects and their analysis.

Harris advocated collecting data regarding relative timing using a *Harris Matrix*, a diagram with rows and columns of boxes spaced apart (Harris 1989:35). The relative timing of the features and stratigraphic formations for any given exposure in an archaeological site can be plotted relative to one another. Only three relationships between units regarding their archaeological stratification are coded: the units have no direct stratigraphic connection, they are in superposition, or the units are correlated as parts of a once-whole deposit or feature interface (Harris 1989:36). A Harris Matrix can become quite elaborate for a complex site with a long occupation history, such as a Near Eastern tell with multiple episodes of construction, intrusive features including burials, destruction, and remodeling brought about by a succession of cultural groups. Each separate exposure also has its own local history that must be considered for the overall site formation history and stratigraphic ordering. Recording the relative timing history of a bone or set of bones from a forensic case is rarely so complicated, with often only a succession of three or four clear taphonomic effects from different postmortem phases to decipher.

A further common precedent in forensic analysis regarding the relative temporal order of changes to a bone is Puppe's Rule, which states that the intersecting fractures on a bone can be used to determine their relative timing (Madea and Staak 1988; Puppe 1903, 1908); a fracture line terminating at another fracture line must have formed after that intersected fracture line. Puppe's Rule applies, however, to perimortem trauma instead of postmortem changes. By examining the intersecting fractures on a cranial vault, for example, one can determine the relative timing of multiple gunshot wounds or blunt force impacts. By observing that fracture lines do not jump across other fracture lines as a material property of bone, a logical reasoning chain that is simple in concept but in some cases difficult to apply in cases of highly fragmented remains to reconstruct the sequence of perimortem events. Forensic anthropologists' experience with trauma analysis can be applied using much of the same reasoning processes to their analysis of the relative timing of postmortem changes.

Laws of Taphonomic Relative Timing

These laws (Pokines 2021) are derived from the geological/archaeological laws discussed above and codified by Harris (1975, 1977, 1979, 1989) and largely are extensions of the same logic to the sequencing of taphonomic effects that have accrued on the same bone or set of remains. They also consider common human and nonhuman behavior regarding postmortem timing, such as scavenging carnivores being more interested in fresh than dry bones, and rodents preferring to gnaw on dry bones to sharpen their incisors. Behavior patterns therefore are integral to the relative timing of postmortem events, but the bones themselves, through overlapping taphonomic effects, encode their own postmortem history (Chapter 1).

The Law of Taphonomic Superposition

> Taphonomic effects that overlie or remove all or part of other taphonomic effects must have occurred later during the postmortem interval.
>
> **(Pokines 2021:4)**

The law of taphonomic superposition derives from the stratigraphic law of superposition and applies in common usage to staining (from sediments, corroding minerals, etc.) of bone surfaces overlying another effect; if staining appears on top of a surface, for example, then that surface must have been formed prior to the staining. This assumes, which in most cases is correct, that staining to bone is superficial (Huculak and Rogers 2009; Pollock et al. 2019; Chapter 12) and does not penetrate deep enough into a bone that an exposed fracture surface, for example, was already modified by deeply penetrating staining. An exception occurs with fat staining, which emerges from the bone's interior and has the capacity to penetrate all through the cortical bone.

This law is especially important regarding the formation of possible perimortem trauma. If fractured, cut, or sawn bone areas have the same staining as unaltered adjacent bone, then the fractured/cut/sawn areas must have been formed prior to the staining. This information regarding temporal sequence does not indicate that the bone damage must have happened during the perimortem interval, only that the damage occurred prior to the staining. While such damage often does occur perimortem, the information supplied by the staining alone is not conclusive regarding its absolute timing, only its relative timing. Bones do fracture during the PMI, such as buried bones fracturing under sediment pressure, and the newly formed but postmortem fracture surface may have decades prior to analysis to take on sediment staining that is indistinguishable from bone surfaces that were in contact with the sediments during the entire span of burial.

Other taphonomic processes besides staining that affect broad areas of bone surfaces are applicable to this law. Abrasion of bones that causes rounding in water environments (Fernández-Jalvo and Andrews 2003, 2016; Pokines and Higgs 2015; Chapters 6 and 7) often affects multiple bone surfaces at once. For these surfaces to become rounded, they must have been formed prior to the rounding: a fractured surface that displays rounding from abrasion must have formed prior to that abrasion. In some cases, a bone immersed in a marine environment is fractured by agitation in that environment (Pokines et al. 2020; Chapter 7), and the break surfaces formed undergo subsequent rounding. Additional agitation may fracture portions of the already rounded surface again, creating a new break surface with sharp boundaries; these sharp boundaries may then undergo additional rounding (Figure 20.1). A given bone therefore may record multiple postmortem stages of taphonomic effects. Subsequent abrasion is also detectable on previously sawn surfaces, as their flat kerf margins get rounded.

Other processes that affect broad surfaces of bone besides staining, including subaerial weathering (Behrensmeyer 1978; Chapter 11), can fall under this law, as the surface cracking and sun bleaching from this process can overlie other taphonomic effects, including break surfaces or scavenger gnawing (Chapters 9 and 18). Colonizing life forms also adhere to bone surfaces and therefore have the potential to overlie previous taphonomic effects (Chapter 7). Repurposing of former anatomical teaching specimens is common (Chapter 8), so the accrual of later taphonomic effects is also common, through the phases of initial preparation, teaching display/use, then turning the object into an item of personal display or ritual use.

The Law of Taphonomic Positional Aspect Discontinuity

> If a taphonomic effect that must have formed with a bone in a certain positional aspect is no longer in alignment with that position, then the bone must have been moved after that taphonomic effect formed.
>
> **(Pokines 2021:5)**

The law of taphonomic positional aspect discontinuity derives from the stratigraphic law of original horizontality. Bones are often deposited on a surface and then stay in that approximate position for many years, thus presenting one surface in contact with the ground,

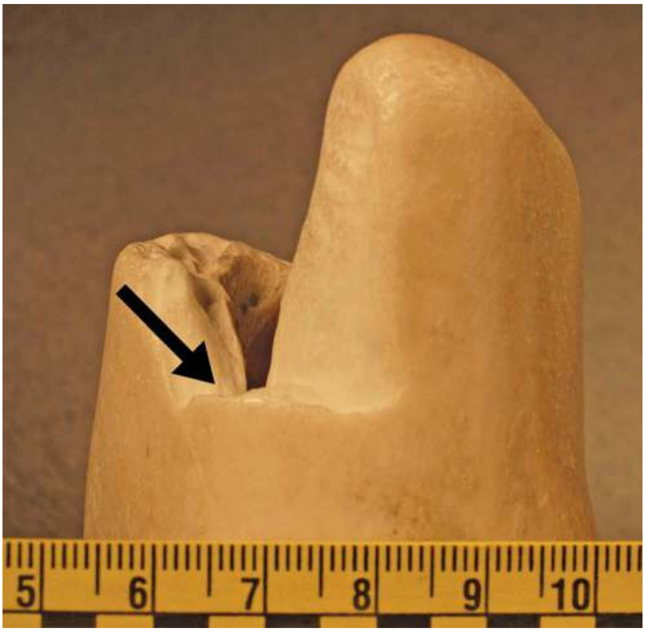

Figure 20.1 A cattle (*Bos taurus*) distal humerus from a marine context, showing marine bleaching and margins rounded from abrasion. A portion (arrow) has fractured more recently than other, more rounded areas. The scale is in cm.

accruing taphonomic effects similar to buried bone (Chapter 5) including sediment staining (Figure 20.2), adhering sediments, and plant root etching, and one surface exposed to the air, accruing taphonomic common taphonomic effects that include subaerial weathering, diffuse green algae staining, lichens (Chapter 11, Figure 11.16) or moss growth, or organic staining from the breakdown of humus (Chapter 12, Figures 12.13 and 12.14). The

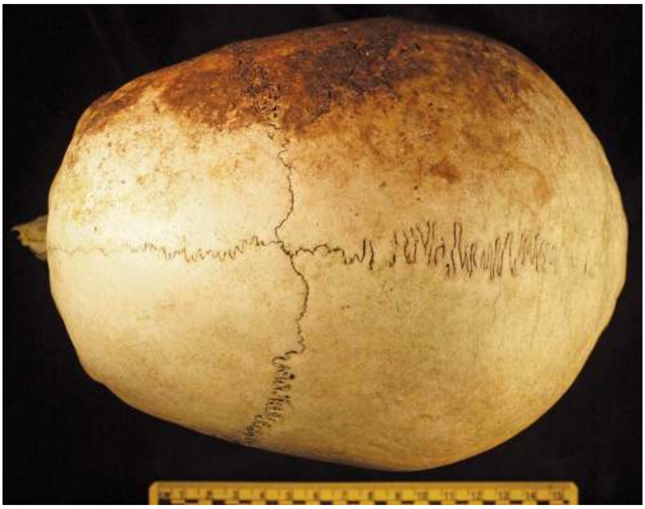

Figure 20.2 Cranium with differential soil staining, indicating that the right side spent significant time in contact with the ground surface; locating this cranium with the right side up would indicate that it had been moved. The scale is in cm.

bone's relationship to gravity therefore plays a key (but not the only) role in the overall patterning of these effects and their different locations on the bone. If the bone is no longer in proper orientation with the portion of the environment that caused these effects, then some force must have moved the bone prior to discovery. While this law manifests itself commonly in the cases of terrestrial surface deposition, it also applies to other situations not wholly governed by gravity/horizontal deposition, so it differs in this aspect from the stratigraphic law of original horizontality.

Other situations affected by gravity where this taphonomic law applies include the formation of coffin wear on bones (Chapter 5, Figures 5.7–5.15). Coffin wear is characterized by flattened areas on bones in a coffin environment where acidic ground water pools, and sediment pressure from coffin collapse also may play a role. It hence normally manifests on the downward surfaces of bones lying against the coffin floor (Pokines et al. 2016), although some exceptions are known to occur from contact with other parts of the coffin (Schultz et al. 2003). Displacement from the orientation in which the coffin wear formed indicates some disturbance of the remains occurred after the coffin wear formation. Water lines are also common on the endocranial surfaces of coffin crania and also indicate their orientation relative to pooling water, often aligning with areas of coffin wear on the crania (Chapter 5, Figures 5.16 and 5.23); these lines can indicate later displacement in the same way that coffin wear can. Stains from the decomposition of brain tissue forming distinct lines within crania decomposing in terrestrial surface environments also can indicate the orientation of that cranium relative to gravity and any subsequent displacement.

This taphonomic law does not apply to processes affecting bone from all directions at once, such as the bleaching that can occur to bones in marine environments (Chapter 7, Figure 7.2). Bones partially buried in marine environments, however, can form sediment lines that indicate the bone orientation during this deposition phase. This may be accompanied by the colonization of marine organisms on the exposed portions (Figure 20.3); while less exact regarding orientation relative to the ocean floor, their presence does indicate which portion of a bone was exposed. Localized mineral staining (Chapter 12, Figures 12.9–12.11) from known sources could indicate bone orientation but could conceivably occur in any direction independent of gravity. In these cases, the later displacement of the bone might be indicated by its separation from the source of staining, regardless of what the relative orientation of the bone and staining agent were previously.

This law also may apply in cases of intact bodies that have undergone livor mortis, where discoloration is caused by blood settling into the lower portions after the heart can no longer pump blood (Chapter 3). Subsequent movement of the body may be detectable by the darkened areas being out of place relative to gravity. Positional changes also may be detectable due to rigor mortis, where the body has become rigid after death and conformed to a particular underlying shape. Subsequent movement may be indicated by limbs positioned opposed to gravity or supporting objects.

The Law of Taphonomic Original Continuity

> A taphonomic effect to a bone surface involving some aspect of color change or other broad surface alteration that is abruptly halted normally must have had some of its original extent removed by a later taphonomic effect. A corollary is that two bones with a continuous

Figure 20.3 Acorn barnacles colonizing one portion of a cranium, indicating that it was deposited upside down on the ocean floor. Note also the dark area of sediment staining, further indicating that the superior left vault was the portion in contact with the ocean floor. The scale is in cm.

> Taphonomic effect must have been articulated when that effect was formed, especially where this articulation protected their adjoining surfaces from the causal taphonomic process.
>
> **(Pokines 2021:5)**

The law of taphonomic original continuity derives from the stratigraphic law of original continuity and often indicates the opposite relative timing described by the law of taphonomic superposition. If areas of unstained bone, for example, have been exposed directly adjacent to stained bone, then the taphonomic process that formed the unstained area must have occurred second. Staining in this case also applied to bleaching, and other effects accruing over a broad surface area like marine abrasion may also apply. Taphonomic processes that remove areas of surface staining include breakage/butchery and scavenger gnawing (Chapters 9 and 18). While staining from sources including sediments or decomposition do not have to accrue uniformly over a bone, it is rare for them to terminate abruptly at a fracture margin. The staining would be expected to continue onto the exposed break surface if it occurred after the fracture. Color change caused by an adhering substance, including oxidizing minerals (Chapter 12, Figure 12.9), can be more abrupt in their boundaries, so information regarding relative timing may not be present. Adhering colonizing organisms, such as acorn barnacles (Chapter 7, Figures 7.12., 7.13, 7.15, and 7.16) also can leave behind abrupt margins where their natural adhesive anchors extend. Sources of color change that penetrate deeply through bone, including fat leaching and carbonization (Chapter 14), can occur before or after a break surface has been formed, although more subtle color differences in the latter case may indicate post-burning breakage. The taphonomic process that formed the surface effect therefore must be understood while avoiding blanket application of this law. In general, abrupt termination of many taphonomic effects indicates that some portion of the bone was removed after those effects were accrued.

The perimortem or postmortem origin of fracturing may be determined by this law in some cases. Where a break surface exposes paler or natural bone color (Schafer 2001) and the adjacent, unfractured bone is unstained, the break surface must have been formed during the PMI. The opposite (i.e., that stained break surfaces must have occurred while the bone was fresh), however, cannot be assumed (Ubelaker and Adams 1995), so other indicators of fresh break surface morphology (Chapter 13) must be considered.

As indicated above, subaerial weathering often affects broad surfaces of a bone through a pattern of sun bleaching and gradually more invasive cracking as it proceeds over multiple years (Beary 2005; Behrensmeyer 1978; Pokines et al. 2018). In its early stages, subaerial weathering can be superficial (Chapter 11), but areas affected on the bone do not normally terminate abruptly except in cases where the bone was partially buried while the exposed portion was affected (Figure 20.4). Subaerial weathering effects can blend so gradually in their lateral extent that an individual bone often has multiple identifiable stages present at once (Behrensmeyer 1978; Lyman and Fox 1997; see also Chapter 11, Figure 11.5). Abrupt terminations are normally indicators that another, later effect has removed part of the weathered bone.

Other processes besides breakage expose unstained bone and can be determined to have occurred later in the PMI. Just as traces of carnivore gnawing often occur early after death, and the tooth-marked areas (Chapters 9 and 18) later take on soil staining like the adjacent areas of unmarked bone, some gnawing typically occurs later during the PMI,

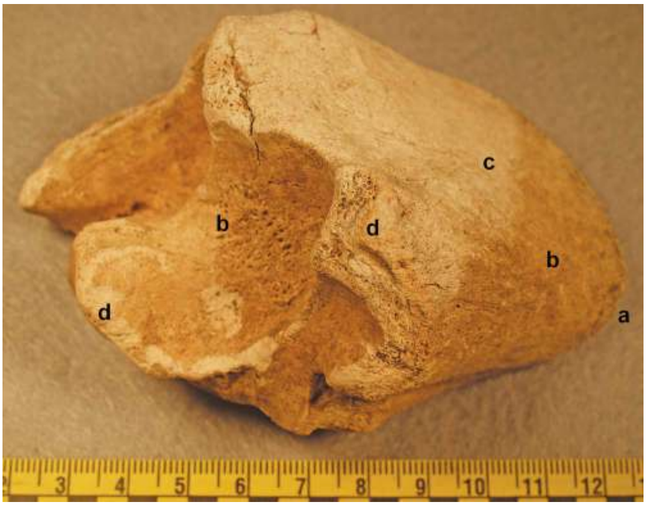

Figure 20.4 Distal cattle (*Bos taurus*) tibia exhibiting at least four taphonomic stages: (a) the shaft was machine butchered obliquely; (b) the tibia was buried and took on soil staining and adhering sediments while accruing acidic soil corrosion; (c) the tibia got partially unburied and developed sun-bleaching along a clear demarcation; and (d) some postmortem breakage removed portions of stained and sun-bleached areas. The scale is in cm.

Figure 20.5 Dry, weathered cranial vault fragment that was then gnawed on by a dog (*Canis familiaris*), leaving multiple striations that exposed the underlying beige bone which therefore must be later in the postmortem sequence.

especially rodent dry-bone gnawing (Chapter 9). It is also common for there to be separate, discernible phases of rodent gnawing, some of which underlie surface staining and some of which overlie it (i.e., have removed areas of it, exposing unstained underlying bone). Gnawing after staining has occurred also happens in some cases by carnivores that are likely testing a long-exposed bone as a food source, find it lacking in nutritional interest, and abandon it (Figure 20.5). Carnivore gnawing cannot be assumed to have occurred only when a bone was in a fresh state, and the examination of the tooth mark and staining pattern can indicate their correct relative timing. As indicated above, staining is often superficial, but rodent gnawing in its early stages can be so superficial as to not penetrate the stained zone fully into underlying unstained bone (Pokines et al. 2017). In these situations, the tooth marks may appear to have been formed prior to the staining, but close examination will reveal their later timing (Figure 20.6).

The law of taphonomic original continuity also applies to articulation between bones or between and unfused epiphysis and a bone. Some taphonomic effects can accrue simultaneously to the articulated sets of bones or epiphyses/bones such that their disarticulation later in the PMI can be determined. These situations can include mineral oxides forming matching stains on adjacent bones (Morris 1981) or unique patterns of sediment staining on buried remains. Applications of this law also includes joint shielding during thermal alteration (Devlin and Herrmann 2008; Symes et al. 2008; Chapter 14, Figure 14.7), in situations where it can be expected that the unaltered area would not have been so if the two bones were not in articulation at the time of the burning. Thermal alteration of sufficient intensity and duration, however, will eventually overcome the joint shielding, so this set of observations will no longer apply to thoroughly cremated remains. Articulations also may shield bones from other effects, including gunshot trauma, so it may be possible to determine that this type of alteration occurred to already dried and disarticulated bones in rare cases (Mann and Owsley 1992).

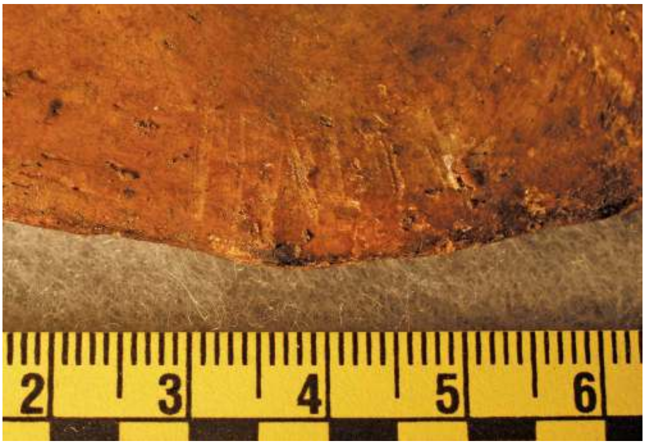

Figure 20.6 Rodent dry-bone gnawing to an innominate; the faint striations have not fully penetrated the surface staining and were formed after the staining. Shallow tooth marks such as these can be mistaken for having been formed first, followed by the staining. The scale is in cm. (From Pokines 2021:7; used with permission, *Forensic Anthropology*/University of Florida Press.)

The Law of Taphonomic Succession

> A taphonomic effect can have one of three relationships to another taphonomic effect: it can predate it, postdate it, or be contemporaneous with it, as with the relationships between layers in an archaeological site, and the succession of these changes is ordered both by the physical contact of these effects and surmised through typical human and nonhuman behavior
>
> **(Pokines 2021:8)**

The law of taphonomic succession is derived from the law of stratigraphical succession and indicates that postmortem histories of bones are built from the direct relationships between different taphonomic effects, chained together. This law also indicates that some taphonomic effects have an unknown relationship to each other or are known commonly to form over simultaneous portions of the PMI with other effects. Examples of these sequences are presented below; while common, they are just a few of the possibilities that may be encountered during forensic anthropological casework.

Many of the taphonomic effects that cannot be clearly sorted in terms of relative timing accrue gradually and at the same time as other environmental or chemical effects as opposed to the individual actions of different species. In marine environments (Pokines and Higgs 2015; Chapter 7), these gradual processes include abrasion leading to rounding, bleaching from saltwater immersion, leaching of fat contents, adipocere formation, and mineral staining; all can proceed at the same time, largely independently. Abrasion, however, can remove some areas of mineral staining around exposed margins, or abraded areas can be covered by mineral staining, so some relative temporal ordering can occur (Figure 20.7). Abrasion also can expose adipocere that has already formed in pore spaces (Chapter 7, Figure 7.1). Organisms often colonize areas and overlie other taphonomic effects, indicating their relative timing (Figure 20.7). In terrestrial environments, simultaneous processes include sediment staining, acidic soil corrosion, and plant root etching (for the downward side) and subaerial weathering and algae/moss/lichens growth on the exposed side.

Figure 20.7 A cattle (*Bos taurus*) distal femur from a marine environment showing, in relative order: dark surface staining, colonization by small acorn barnacles (small, white objects), then removal of stained/colonized areas by marine abrasion, leaving behind paler, exposed cancellous bone. The scale is in cm.

Some taphonomic processes also recur at discrete intervals during the PMI, complicating the postmortem history. As indicated above, rodent dry-bone gnawing is often episodic, occurring before and after other taphonomic effects, as a dry bone offers a useful resource for many years during terrestrial surface exposure (Pokines 2015b, 2016; Pokines et al. 2016; Chapter 9). This gnawing can overlie perimortem fracture surfaces, especially as these surfaces may have narrower margins that are more easily gnawed by smaller species (Pokines et al. 2017).

Terrestrial environments often induce multiple overlapping taphonomic effects, in part due to the multitude of scavengers that are attracted to the resource of fresh remains (Pokines 2016, 2018; Pokines and Pollock 2018; Chapter 9). Primary reduction of the soft tissue can occur via arthropod activity (Chapter 3) or through large vertebrate scavengers (Haglund 1997; Haglund et al. 1989). In the latter case, gnawing damage can be extensive (Pobiner 2007; Pobiner et al. 2020). In terms of general scavenger behavior, the taphonomic effects of bone gnawing by carnivores tend to accrue earlier in sequence, as these species are attracted to fresh remains to obtain associated exterior soft tissue but also the fat content of the bones (Chapter 9). Carnivore tooth marks therefore tend to be early in sequence, although exceptions occur as noted above where a carnivore will test a dry bone (Figure 20.5). Sediment staining of the now-abandoned bone lying on the terrestrial surface often occurs next, which may include decomposition staining from residual soft tissue. Sun-bleaching can occur next as the bone is exposed, making it more attractive for rodent dry-bone gnawing, which often removes stained areas that themselves were covering carnivore gnawing. Figure 20.8 illustrates a three-part sequence for a terrestrial case, where fracturing and crenellation of margins from carnivore gnawing occurred first, followed by soil staining over the exposed surfaces, with areas of rodent dry-bone gnawing on the stained bone (and in some areas, on the carnivore-exposed margins) exposing pale underlying bone.

Former cemetery remains can have complex histories, as they often come under forensic examination because of disturbance of unmarked graves (Pokines et al. 2016). The multiple

Figure 20.8 Right clavicle (top) and left radius (bottom) from the same terrestrial surface case, showing a three-part relative timing sequence: (a) fracturing and crenellation of margins from carnivore gnawing, that subsequently became soil-stained, followed by (b) areas of rodent dry-bone gnawing exposing pale underlying bone. The scales are in cm.

postmortem phases that can leave behind taphonomic effects (Chapter 5) can include: (1) autopsy; (2) embalming; (3) decomposition within the coffin, with bone staining, plant root growth, and coffin wear; (4) dispersal through accidental excavation, especially where a wooden coffin has broken down, with impact damage by excavating machinery (Chapter 17); (5) surface deposition with the formation of subaerial weathering and scavenger gnawing (Chapters 9 and 11); and further complicated by (6) repurposing discovered bones into display or ritual items (Chapter 8); and (7) the effects of long-term curation if the bones have been in storage for years in a forensic facility awaiting final disposition. The taphonomic effects from these phases can overwrite the effects from previous phases. Figure 20.9 shows a proximal right femur with a (surprisingly common) postmortem history. The head/neck displays highly developed coffin wear, with a flat area of damage to the posterior surface; the distal end (not shown) also has this damage pattern. The overall texture of the bone is chalky, which is also consistent with long-term burial and a breakdown of organic content. The coffin wear is overlain by sediment staining, sediment adhesion, and subaerial weathering, including sun-bleaching. The subaerial weathering effects are likely the latest in sequence, since the other effects would accrue while buried; the event causing exhumation and dumping on the terrestrial surface must have occurred in between, although some sediment adhesion could accrue while lying on the surface. The bone also has patches of green algae, which would form at the same time as the weathering effects, during surface exposure, as light and moisture are necessary. Areas of bone were then removed by rodent dry-bone gnawing (Chapter 9), exposing patches of pale underlying bone. This case was then reported to law enforcement and underwent forensic anthropological analysis, so its postmortem history did not accrue additional outdoor effects. Other cases include the use for former cemetery remains, sometimes exhumed directly for use in ritual, including Palo Mayombe (Winburn et al. 2016, 2017; Chapter 8). Figure 20.10 shows a similar sequence to the above with a former cemetery cranium exhibiting at least three

Figure 20.9 Proximal right femur showing highly developed coffin wear on the posterior head/neck and an overall chalky texture consistent with long-term burial and a breakdown of organic content. The coffin wear is overlain by sediment staining, sediment adhesion, and subaerial weathering effects, which likely occurred last among these effects, although some sediment adhesion could accrue while lying on the surface. The patches of green algae likely would form at the same time as the subaerial weathering effects. Areas of bone were then removed by rodent dry-bone gnawing, exposing patches of pale underlying bone. The scale is in cm.

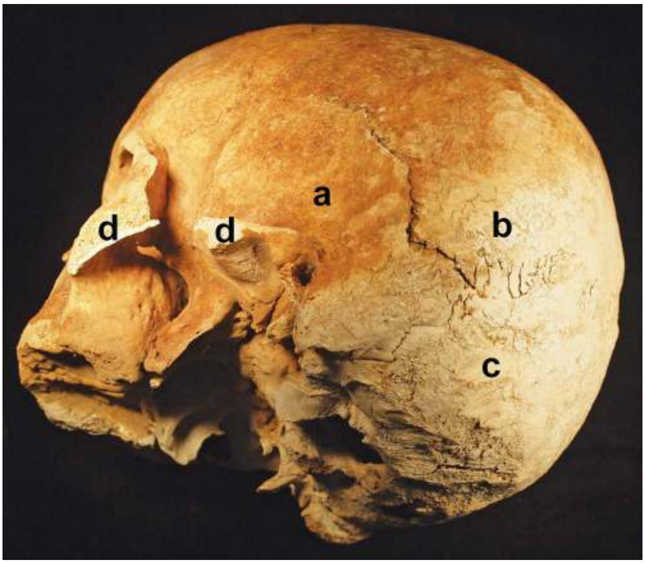

Figure 20.10 Former cemetery cranium exhibiting at least three taphonomic stages: (a) burial in the coffin environment or later soil contact caused brown staining and other cemetery effects; (b) the cranium got partially unburied and developed sun bleaching and fine surface cracking from subaerial weathering along a clear demarcation; (c) rodent dry-bone gnawing; and (d) postmortem breakage removed portions of weathered and stained bone, respectively, exposing the underlying bone. Since (c) and (d) do not overlie each other, the relative timing between the two is unknown.

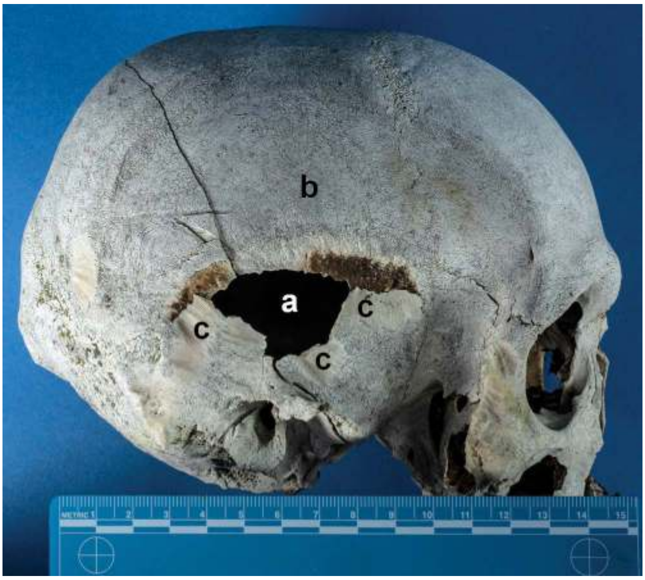

Figure 20.11 Cranium with (a) gunshot exit wound with radiating fractures on the right vault followed by (b) sun bleaching and fine surface cracking from subaerial weathering, with (c) some of the margins exposed by trauma later subjected to rodent dry-bone gnawing. The scale is in cm. (Image courtesy of Diane France.)

taphonomic stages. Coffin burial or later direct soil contact formed brown surface staining and other effects, including some warping and chalky surface texture. The cranium then got partially unburied and developed sun-bleaching and fine surface cracking along a clear demarcation, while the rest of the cranium remained buried. Rodent dry-bone gnawing removed portions of the weathered bone, and postmortem breakage removed portions of stained bone, exposing the underlying bone. The relative timing between the last two effects is unknown, and they could have occurred in either order. As the fractured bone surfaces were entirely unstained, they may have occurred upon discovery of the cranium and its subsequent reporting to law enforcement.

Figure 20.11 illustrates how taphonomic effects can accrue in sequence after perimortem trauma has occurred and add support to the conclusion that the damage to the bone must have occurred relatively early in the perimortem/postmortem sequence. In this example, a cranium had undergone perimortem trauma in the form of a gunshot wound, with the exit on the right side. The trauma was followed by sun-bleaching and fine surface cracking from subaerial weathering. Some of the margins exposed by trauma were later subjected to rodent dry-bone gnawing. Rodent dry-bone gnawing favors margins narrow enough for these small species to reach their mandibles/maxillae around (Chapter 9), so the trauma has made portions of the vault more accessible to this type of behavior.

Former anatomical teaching specimens (Pokines 2015c, 2018, 2020; Chapter 8) are often repurposed for ritual or display, and the taphonomic effects from this later phase include thermal alteration and wax from use as candle holders, painting, and chopping marks (to make them appear to have a martial origin to increase their value as an antique for sale). Their origin as anatomical teaching specimens will be detectable commonly from the presence of vault sectioning, drilling, hardware, labeling, marking, patina, and handling damage that will be overlain by the repurposing effects (Chapter 8, Figures 8.5 and 8.6). In such cases, taphonomic effects often can be grouped only to phase, as, for example, the exact sequence of anatomical preparation effects may not be known other than maceration would normally precede sectioning and drilling for hardware attachment; signs of use for teaching such as breakage, patina, and pencil marks would come next though not necessarily in a clear order within their phase; then signs of repurposing would come last, after their use in teaching had ended.

Conclusions

The use of these relative timing laws to reconstruct the postmortem history of a set of forensic remains can be a standard part of taphonomic analysis for every case. These histories are sometimes not straightforward, and thorough analysis requires an interpretation of all the taphonomic effects observed. This is especially important where there is any question of trauma to bone, and a forensic anthropologist should be prepared to testify on how they have determined that a given alteration to bone was consistent with occurring while the bone was still fresh (Ubelaker and Adams 1995; Wheatley 2008; Wieberg and Wescott 2008; Chapter 13). It is also important for the processing of a case and its final disposition (Chapter 1), as much of this classification relies upon knowing if a set of remains passed through more than one type of depositional environment between death and analysis and in some cases which taphonomic effects are more common to nonhuman than human remains (Crabtree and Campana 2008; Pokines 2015a, 2016). The chain of discernible taphonomic effects arranged temporally is often not highly complicated in single-component deposition sites but still may clarify what events occurred between the time of body deposition and analysis, including patterns of bone dispersal (Chapters 9 and 16) and aiding in choosing the methods used to recover the scene (Chapter 17). Taphonomic histories therefore bridge multiple portions of scene processing, analysis, and interpretation of remains.

Acknowledgments

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References

Beary, M. O. (2005) *Taphonomic Effects of UV Light on Bone Surface: An Experimental Approach*. M.A. Thesis, Mercyhurst College, Erie, PA.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Palaeobiology* 4(2):150–162.

Behrensmeyer, A. K. (1991) Terrestrial vertebrate accumulations. In *Taphonomy: Releasing the Data Locked in the Fossil Record* ed. by P. A. Allison and D. E. G. Briggs, pp. 291–335. Springer, Dordrecht.

Behrensmeyer, A. K. (2008) Paleoenvironmental context of the Pliocene A. L. 333 "First Family" hominin locality, Hadar Formation, Ethiopia. In *The Geological Context of Human Evolution in the Horn of Africa* ed. by J. Quade and J. G. Wynn, pp. 203–214. Geological Society of America, Special Paper 446, Boulder, CO.

Behrensmeyer, A. K., E. H. Harmon, and W. H. Kimbel (2003) Environmental context and taphonomy of the A. L. 333 Locality, Hadar, Ethiopia. *Journal of Vertebrate Paleontology* 23(S3):33A.

Behrensmeyer, A. K., and S. M. Kidwell (1985) Taphonomy's contributions to paleobiology. *Paleobiology* 11(1):105–119.

Behrensmeyer, A. K., and K. E. Reed (2013) Reconstructing the habitats of *Australopithecus*: Paleoenvironments, site taphonomy, and faunas. In *The Paleobiology of Australopithecus* ed. by K. E. Reed, J. G. Fleagle, and R. E. Leakey, pp. 41–60. Springer, Dordrecht.

Berger, L. R. (2006) Predatory bird damage to the Taung-type skull of *Australopithecus africanus* Dart 1925. *American Journal of Physical Anthropology* 131:166–168.

Berger, L. R., and W. S. McGraw (2007) Further evidence for eagle predation of, and feeding damage on, the Taung child. *South African Journal of Science* 103(11–12):496–498.

Binford, L. R. (1981) *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Churchill, S. E., R. G. Franciscus, H. A. McKean-Peraza, J. A. Daniel, and B. R. Warren (2009) Shanidar 3 Neandertal rib puncture wound and Paleolithic weaponry. *Journal of Human Evolution* 57(2):163–178.

Crabtree, P. J., and D. V. Campana (2008) Traces of butchery and bone working. In *Comparative Skeletal Anatomy* ed. by B. J. Adams and P. J. Crabtree, pp. 323–345. Humana Press, Totowa, NJ.

Davidson, I., and S. Solomon (1990) Was OH7 the victim of a crocodile attack? In *Problem Solving in Taphonomy: Archaeological and Palaeontological Studies from Europe, Africa and Oceania* ed. by S. Solomon, I. Davidson, and D. Watson, 197–206. Tempus, St. Lucia, Qld, Australia.

Devlin, J. B., and N. P. Herrmann (2008) Bone color as an interpretive tool of the depositional history of archaeological cremains. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 109–128. Academic Press, Amsterdam.

Dirkmaat, D. C., and L. L. Cabo (2016) Forensic archaeology and forensic taphonomy: Basic considerations of how to properly process and interpret the outdoor forensic scene. *Academic Forensic Pathology* 6(3):439–454.

Domínguez-Rodrigo, M. (2002) Hunting and scavenging by early humans: The state of the debate. *Journal of World Prehistory* 16(1):1–54.

Donovan, S. K., ed. (1991) *The Processes of Fossilization*. Columbia University Press, New York.

Efremov, J. A. (1940) Taphonomy: New branch of paleontology. *Pan-American Geologist* 74(2):81–93.

Fernández-Jalvo, Y., and P. Andrews (2003) Experimental effects of water abrasion on bone fragments. *Journal of Taphonomy* 1(3):147–163.

Fernández-Jalvo, Y., and P. Andrews (2016) *Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification*. Springer, Dordrecht.

Haglund, W. D. (1993) Disappearance of soft tissue and the disarticulation of human remains from aqueous environments. *Journal of Forensic Sciences* 38(4):806–815.

Haglund, W. D. (1997) Dogs and coyotes: Postmortem involvement with human remains. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 367–381. CRC Press, Boca Raton, FL.

Haglund, W. D., D. T. Reay, and D. R. Swindler (1989) Canid scavenging/disarticulation sequence of human remains in the Pacific Northwest. *Journal of Forensic Sciences* 34(3):587–606.

Haglund, W. D., and M. H. Sorg, eds. (1997) *Forensic Taphonomy: The Postmortem Fate of Human Remains*. CRC Press, Boca Raton, FL.

Haglund, W. D., and M. H. Sorg (2002) Human remains in water environments. In *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives* ed. by W. D. Haglund and M. H. Sorg, pp. 201–218. CRC Press, Boca Raton, FL.

Harris, E. C. (1975) The stratigraphic sequence: A question of time. *World Archaeology* 7(1):109–121.

Harris, E. C. (1977) Units of archaeological stratification. *Norwegian Archaeological Review* 10:84–94.

Harris, E. C. (1979) The laws of archaeological stratigraphy. *World Archaeology* 11(1):111–117.

Harris, E. C. (1989) *Principles of Archaeological Stratigraphy* (2nd ed.). Academic Press, London.

Haynes, G. (1980) Prey bones and predators: Potential ecologic information from analysis of bone sites. *OSSA* 7:75–97.

Hill, A., and A. K. Behrensmeyer (1984) Disarticulation patterns of some modern East African mammals. *Paleobiology* 10(3):366–376.

Huculak, M. A., and T. L. Rogers (2009) Reconstructing the sequence of events surrounding body disposition based on color staining of bone. *Journal of Forensic Sciences* 54(5):979–984.

Hutton, J. (1788) *The Theory of the Earth; or, an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe*. Transactions of the Royal Society of Edinburgh, Vol. 1, Edinburgh, Scotland.

L'Abbé, E. N., S. A. Symes, J. T. Pokines, L. L. Cabo, K. E. Stull, S. Kuo, D. E. Raymonds, P. S. Randolph-Quinney, and L. R. Berger (2015) A fatal fall from height, the cause of death of Malapa Hominins 1 and 2. *(Nature) Scientific Reports* 5:15120. DOI: 10.1038/srep15120.

Lyell, C. (1830–1833) *Principles of Geology* (3 Vols.). J. Murray, London.

Lyman, R. L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

Lyman, R. L., and G. L. Fox (1997) A critical evaluation of bone weathering as an indication of bone assemblage formation. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 223–247. CRC Press, Boca Raton, FL.

Madea, B., and M. Staak (1988) Determination of the sequence of gunshot wounds of the skull. *Journal of Forensic Science Society* 28(5–6):321–328.

Mann, R. W., and D. W. Owsley (1992) Human osteology: Key to the sequence of events in a postmortem shooting. *Journal of Forensic Sciences* 37(5):1386–1392.

Martin, R. E. (1999) *Taphonomy: A Process Approach*. Cambridge University Press, Cambridge.

Morris, A. G. (1981) Copper discolouration of bone and the incidence of copper artefacts with human burials in South Africa. *South African Archaeological Bulletin* 36(133):36–42.

National Missing and Unidentified Persons System (NamUs) (2021) (Home page.) Electronic document, http://namus.gov/, accessed 14 March 2021.

Njau, J. K., and R. J. Blumenschine (2012) Crocodylian and mammalian carnivore feeding traces on hominid fossils from FLK 22 and FLK NN 3, Plio-Pleistocene, Olduvai Gorge, Tanzania. *Journal of Human Evolution* 63(2):408–417.

Oldenburg, H. (1671) *The Prodromus to a Dissertation Concerning Solids Naturally Contained within Solids, by Nicolaus Steno* (English translation). F. Winter, London.

Pante, M. C., R. J. Blumenschine, S. D. Capaldo, and R. S. Scott (2012) Validation of bone surface modification models for inferring fossil hominin and carnivore feeding interactions, with reapplication to FLK 22, Olduvai Gorge, Tanzania. *Journal of Human Evolution* 63(2): 395–407.

Pickering, T. R., M. Domínguez-Rodrigo, C. P. Egeland, and C. K. Brain (2004) Beyond leopards: Tooth marks and the contribution of multiple carnivore taxa to the accumulation of the Swartkrans Member 3 fossil assemblage. *Journal of Human Evolution* 46(5):595–604.

Pobiner, B. L. (2007) *Hominin-Carnivore Interactions: Evidence from Modern Carnivore Bone Modification and Early Pleistocene Archaeofaunas (Koobi Fora, Kenya; Olduvai Gorge, Tanzania)*. Ph.D. Dissertation, Rutgers University, Newark, NJ.

Pobiner, B. L., L. Dumouchel, and J. Parkinson (2020) A new semi-quantitative method for coding carnivore chewing damage with an application to modern African lion-damaged bones. *Palaios* 35:302–315.

Pokines, J. T. (2015a) Identification of nonhuman remains received in a medical examiner setting. *Journal of Forensic Identification* 65(3):223–246.

Pokines, J. T. (2015b) Taphonomic alterations by the rodent species woodland vole (*Microtus pinetorum*) upon human skeletal remains. *Forensic Science International* 257:e16–e19.

Pokines, J. T. (2015c) Taphonomic characteristics of former anatomical teaching specimens received at a Medical Examiner's office. *Journal of Forensic Identification* 65(2):173–195.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T. (2018) Differential diagnosis of the taphonomic histories of common types of forensic osseous remains. *Journal of Forensic Identification* 68(1):87–145.

Pokines, J. T. (2020) The case of the… cases: The flow of the ordinary into a medical examiner's office. In *Case Studies in Forensic Anthropology: Bonified Skeletons* ed. by H. Garvin and N. Langley, pp. 291–302. CRC Press, Boca Raton, FL.

Pokines, J. T. (2021) Laws of taphonomic relative timing and their application to forensic contexts. *Forensic Anthropology* 4(1):1–14.

Pokines, J. T., K. Faillace, J. Berger, D. Pirtle, M. Sharpe, A. Curtis, K. Lombardi, and J. Admans (2018) The effects of repeated wet-dry cycles as a component of bone weathering. *Journal of Archaeological Science: Reports* 17:433–441.

Pokines, J. T., and N. Higgs (2015) Macroscopic taphonomic alterations to human bone in marine environments. *Journal of Forensic Identification* 65(6):953–984.

Pokines, J. T., M. Menschel, S. Mills, E. Janowiak, R. Satish, C. Kincer, and S. Soltani (2020) Experimental formation of marine abrasion on bone and the forensic postmortem interval. *Forensic Anthropology* 3(4):175–189.

Pokines, J. T., and C. Pollock (2018) The small scavenger guild of Massachusetts. *Forensic Anthropology* 1(1):52–67.

Pokines, J. T., S. A. Santana, J. D. Hellar, P. Bian, A. Downs, N. Wells, and M. D. Price (2016) The taphonomic effects of eastern gray squirrel (*Sciurus carolinensis*) gnawing upon bone. *Journal of Forensic Identification* 66(4):349–375.

Pokines, J. T., R. Sussman, M. Gough, C. Ralston, E. McLeod, K. Brun, A. Kearns, and T. L. Moore (2017) Taphonomic analysis of Rodentia and Lagomorpha bone gnawing based upon incisor size. *Journal of Forensic Sciences* 62(1):50–66.

Pokines, J. T., D. P. Zinni, and K. Crowley (2016) Taphonomic patterning of cemetery remains received at the Office of the Chief Medical Examiner, Boston, Massachusetts. *Journal of Forensic Sciences* 61(S1):S71–S81.

Pollock, C., J. T. Pokines, and J. Bethard (2019) Organic staining on bone from exposure to wood and other plant materials. *Forensic Science International* 283:200–210.

Puppe, G. (1908) *Atlas und Grundriß der Gerichtlichen Medizin*. Lehmann, München.

Puppe. G. (1903) Traumatische todesursachen. In *Gerichtliche Medizin: Zwölf Vortrage* ed. by R. Kuttner, pp. 65–84. G. Fischer, Jena, Germany.

Schafer, A. T. (2001) The colour of the human skull. *Forensic Science International* 117:53–56.

Schultz, J., M. Williamson, S. P. Nawrocki, A. Falsetti, and M. Warren (2003) A taphonomic profile to aid in the recognition of human remains from historic and/or cemetery contexts. *Florida Anthropologist* 56(2):141–147.

Smith, W. (1816) *Strata Identified by Organized Fossils, Containing Prints on Colored Paper of the Most Characteristic Specimens in Each Stratum*. W. Arding, London.

Steno, N. (1669) *De Solido intra Solidum Naturaliter Contento Dissertationis Prodromus*. Ex Typographia sub signo Stellae, Florence.

SWGANTH (2013) Taphonomic observations in the postmortem interval. Electronic document, https://www.nist.gov/system/files/documents/2018/03/13/swganth_taphonomic_observations.pdf, accessed 23 April 2021.

Symes, S. A., C. W. Rainwater, E. N. Chapman, D. R. Gipson, and A. L. Piper (2008) Patterned thermal destruction of human remains in a forensic setting. In *The Analysis of Burned Human Remains* ed. by C. W. Schmidt and S. A. Symes, pp. 15–54. Elsevier, Amsterdam.

Trigger, B. G. (1989) *A History of Archaeological Thought*. Cambridge University Press, Cambridge.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–90. CRC Press, Boca Raton, FL.

Ubelaker, D. H., and B. J. Adams (1995) Differentiation of perimortem and postmortem trauma using taphonomic indicators. *Journal of Forensic Sciences* 40(3):509–512.

University of North Texas Center for Human Identification (UNTCHI) (2021) (Home page.) Electronic document, https://www.untchi.org/, accessed 15 March 2021.

Weigelt, J. (1989 [1927]) *Recent Vertebrate Carcasses and Their Paleobiological Implications*. Reprint ed., translated by J. Schaefer. University of Chicago Press, Chicago.

Wheatley, B. P. (2008) Perimortem or postmortem bone fractures? An experimental study of fracture patterns in deer femora. *Journal of Forensic Sciences* 53(1):69–72.

Wieberg, D. A. M., and D. J. Wescott (2008) Estimating the time of long bone fractures: Correlation between postmortem interval, bone moisture content, and blunt force trauma fracture characteristics. *Journal of Forensic Sciences* 53(5):1028–1034.

Winburn, A. P., R. Martinez, and S. K. Schoff (2017) Afro-Cuban ritual use of human remains: Medicolegal considerations. *Journal of Forensic Identification* 67(1):1–30.

Winburn, A. P., S. K. Schoff, and M. W. Warren (2016) Assemblages of the dead: Interpreting the biocultural and taphonomic signature of Afro-Cuban Palo practice in Florida. *Journal of African Diaspora Archaeology and Heritage* 5(1):1–37.

Young, A., N. Márquez-Grant, R. Stillman, M. J. Smith, and A. H. Korstjens (2015) An investigation of red fox (*Vulpes vulpes*) and Eurasian badger (*Meles meles*) scavenging, scattering, and removal of deer remains: Forensic implications and applications. *Journal of Forensic Sciences* 60(S1):S39–S55.

Young, A., R. Stillman, M. J. Smith, and A. H. Korstjens (2014) An experimental study of vertebrate scavenging behavior in a northwest European woodland context. *Journal of Forensic Sciences* 59(5):1333–1342.

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Laboratory and Field Methods in Forensic Taphonomy

21

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Contents

> "There's a Bene Gesserit saying," she said. "You have sayings for everything!" he protested. "You'll like this one," she said. "It goes: 'Do not count a human dead until you've seen his body. And even then you can make a mistake.'"
>
> **—Frank Herbert**
> *Dune*

Introduction

Chapter 1 of this volume discusses the importance of taphonomic analysis in establishing a biological profile. Beyond being one component of forensic anthropological analysis along with sex, age, stature, or ancestry, the final disposition of a case often is based upon its taphonomic origin and postmortem interval (PMI) estimation. Taphonomy therefore is best integrated into the analytical system for case processing, including field recovery, data collection, note taking, photography, and report writing. Some taphonomic data, including dispersal patterns, only can be collected in the field, so this integration begins early in the process (Dirkmaat and Cabo 2016; Ubelaker 1997). In turn, taphonomic awareness also affects the recovery methods themselves, including the distance necessary to search surface scenes based upon the known dispersal distances caused by scavengers in that environment (Chapters 9, 16, and 19) or distances of marine or river transport (Chapters 6 and 7). Appropriate laboratory and field procedures therefore are necessary to achieve these goals and are aided by established note taking guidelines, examples of which are presented here.

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Recording Macroscopic Taphonomic Data

The scale of possible macroscopic taphonomic effects that can be recorded for a forensic case (or to determine that the case is not of police interest; Duhig 2003; Pokines 2020) is reflected throughout the chapters of the current volume. Many other taphonomic effects, not covered here, are possible, and the analyst always must be mindful of taphonomic effects that do not fit any common template. One author (JTP), for example, sometimes encounters arthropod egg casings, insect cocoons, or animal droppings on exposed osseous remains. While their presence is included in the taphonomic notes for a case, these require no substantial analytical process other than those performed by specialists in invertebrate identification, should the information prove useful in estimation of the PMI.

Multiple checklists of taphonomic observations (Tables 21.1–21.3) are presented in this chapter for adaptation by the reader. Table 21.1 presents a long-format checklist of many possible effects that can be adapted to those commonly encountered in a given jurisdiction, and individual analysts are encouraged to adapt the material to their own laboratory analytical systems as best reflects the common cases that they encounter. Individuals working in more arid zones of the USA with many border-crosser deaths, for example, may need to emphasize the presence and degree of desiccated soft tissue to a greater degree, while eliminating taphonomic effects accrued in marine environments. Many excellent sources exist (Allison and Briggs 1991; Bonnichsen and Sorg 1989; Buikstra and Ubelaker 1994; Denys and Patou-Mathis 2014; Donovan 1994; Fernández-Jalvo and Andrews 2016; Fisher 1995; Haglund and Sorg 1997, 2002; Lyman 1994; Martin 1999; Micozzi 1991; Miller 1969, 1975; Morlan 1984; Shipman 1981) that can be used to expand or adapt particular data collection systems for forensic casework based upon individual authors' experiences. In particular, multiple studies of former cemetery remains (Chapter 5) were performed by other researchers (Berryman et al. 1991, 1997; Nawrocki 1995; Rogers 2005; Schultz et al. 2003) in some of the earlier attempts at codifying the taphonomic suites of characteristics for forensic case work, and these sources should be consulted. Researchers also will need access to training and sources (e.g., Wedel and Galloway 2014) regarding perimortem trauma analysis to contrast these alterations more effectively from taphonomic effects.

One author (JTP) uses a two-page macroscopic taphonomic checklist as part of a standardized set of bench notes to record these data for all forensic cases in his jurisdiction (Table 21.2). A summary of the relative timing of effects (Pokines 2021; Chapter 20) should not be an undue encumbrance to taphonomic bench notes due to their simpler nature, and recording these relationships will be necessary for report writing (SWGANTH 2013), as these sequences often do not involve many stages. It must be noted that while laboratory methods are discussed here and in terms of the analysis that a set of skeletal remains will undergo, some data collection can take place in the field if the author was part of the initial recovery.

The reader is also referred to the data collection systems discussed in the other chapters. These include scoring decomposition stage (Chapter 3), marine abrasion stage (Chapter 7), types and degree of gnawing damage (Chapter 9), subaerial weathering stage (Chapter 11), color descriptions (Chapter 12), and types of thermal alterations (Chapter 14). The authors recommend having the stage images and descriptions for subaerial weathering of bone by Behrensmeyer (1978) at hand, and these are reproduced in their entirety in Buikstra and Ubelaker (1994). A complete set of references, printed or electronic, is also necessary for case reference and diagnosis of taphonomic origins, and several are recommended in the reference sections of this volume.

Table 21.1 **Macroscopic Osseous Taphonomy Checklist**

Decompositional
Adhering soft tissue, including hair
Adhering adipocere
Marrow present
Retained decomposition odor
Retained grease texture or organic sheen
Decompositional insect casings/other remains present
Bone Preservational
General state of remains (excellent, good, fair, or poor)
Cortical erosion/exposure of cancellous bone
Cortical exfoliation (bone loss in thin, spalling layers)
Perimortem breakage/fragmentation or trauma
Rounding/battering (erosion/tumbling in an abrasive environment)
Decalcified
Incidental surface striations/scratches
Coffin wear
Surface cracking/longitudinal splitting from drying of bone/teeth
Subaerial weathering (bleaching and cracking; *sensu* Behrensmeyer 1978)
Elemental Patterning
Missing elements (postmortem tooth loss, etc.)
Spatial distribution of elements/articulation
Storage of smaller elements within the cranium (indicating reburial or post-burial movement)
Previous/current commingling
Relationship of field recovery methods (surface survey only, lack of screening, screen mesh size, etc.) to patterning of non-recovered elements
Soil, Burial Substrate, and Mineral
General soil staining
Warping/flattening of elements (especially the cranial vault)
Crushing/compaction from overburden
Adhering/infiltrating sediments
Copper (green), iron (red), calcium (white), manganese (black), or other mineral oxide staining
Vivianite formation
Subfossilization
Fossilization
Concretion
Salt crystal damage (drying of remains from saline environments)
Water staining (presence of a water ring from calcium mineral deposits, color differential line)
Plant/Fungal/Protozoan/Bacterial
Algal presence/staining
Mold presence/staining
Bacteria presence/staining
Dark brown staining from tannins (from leaves or wood, including wooden coffins)
Plant root damage on surfaces
Plant roots still infiltrating/adhering
Accumulation of decomposing leaf litter (humus) within/upon skeletal elements
Other adhering plant taxa (moss, lichens, etc.)

(Continued)

Table 21.1 ***(Continued)*** **Macroscopic Osseous Taphonomy Checklist**

Faunal
Adhering fauna (mollusks, barnacles, etc.)
Carnivore gnawing (tooth marks, crenellation, edge polish, etc.)
Marine organism boring/bioerosion
Human gnawing
Gastric corrosion, winnowing, or windowing of bone
Rodent gnawing
Termite or other arthropod damage
Thermal Alteration
Cooking (translucence, loss of hardness, pot polish, etc.)
Carbonization, calcination, white heat lines, etc.
Cracking patterns from the burning of dry or green bone
Soot accumulation
Melted materials on bone (plastic, etc.)
Cultural Modification
Boot portions/similar adhering
Metal oxidized onto bone
Adhering fabric/other
Adhering oil/other similar
Excavation damage (tool gouges, chatter marks, punctures, etc.)
Plowing damage (deep gouges)
Microabrasion (small irregular striations)
Curation damage/alteration (patina/polish developed from repeated handling, positional wear surfaces or "shelf wear", etc.)
Mounting hardware (screws, pedestal, etc.) or related alteration (drilling)
Accumulation of dust
Accumulation of candle wax
Accumulation of non-decompositional arthropods (arachnids, ants, hornets, etc.) or other taxa
Specimen labeling
Alteration into an implement or other cultural signifier (bone awl, suspension for jewelry, etc.)
Alteration by autopsy (surgical saw marks in typical autopsy locations)
Painting, oiling, smoking, etc.
Bleaching, as in specimen preparation for an anatomical collection
Presence of embalming chemical residue (formalin, etc.)
Machine cutting from butchery (most likely indicating faunal rather than human remains)
Chemical acidic corrosion
Previous writing, labeling, other marking, gluing, taping, or other adhering non-biological (packaging material, preservative, etc.)
Previous analyst reconstruction or other alteration (labeling, gluing, waxing, taping, etc.)
DNA or histological analysis cuts
Bag wear

Table 21.2 Abbreviated Macroscopic Osseous Taphonomy Checklist

General state of remains (excellent, good, fair, or poor)
Green (copper), red (iron), white (calcium), or other mineral staining
Algal staining
General (soil) staining
Retained grease texture or organic sheen
Adhering dried soft tissue, including marrow or adipocere
Surface cracking from drying of waterlogged bone
Subaerial weathering (bleaching and cracking, *sensu* Behrensmeyer 1978)
Thermal alteration (carbonization, calcination, cracking, etc.)
Plant root damage/plant roots still adhering or infiltrating
Other adhering taxa (mold, moss, mollusks, etc.)
Adhering or infiltrating sediments and type (clay, silt, sand, or larger)
Postmortem breakage
Excavation damage (tool marks)
Cortical erosion due to acidic substrate
Cortical exfoliation (bone loss in thin layers)
Marine coastal alteration (rounding, bleaching, etc.)
Writing, labeling, other marking; gluing, taping, packaging or other adhering non-biological
Curation damage/alteration
Carnivore damage
Rodent damage
Other

Laboratory Equipment

The equipment needed for taphonomic examinations is often part of the standard operations in a forensic anthropology laboratory (Walsh-Haney et al. 2008), and additional expense or space is not typically required. Standard hand magnifiers are used to examine for smaller traces on bone, with a binocular microscope also needed in some cases. The stand for the latter should provide sufficient clearance for an entire cranium, as any area of any bone may require low-level microscopic examination.

The open-source *ImageJ* software is useful for measurements of tooth marks and other small taphonomic effects and is available for free download (https://imagej.nih.gov/ij/index.html). The determination of possible mammalian scavengers using the size of their individual tooth marks (Chapter 9) is a more advanced analysis and not required for every case. Microscopic taphonomic analyses requiring sectioning, however, entail significant amounts of equipment, training, and expertise to perform, and these are discussed below.

Additional data collection on a case by case basis of the taphonomic effects described in this volume allows for the broader patterns of taphonomic changes from different environments to emerge and aid in the classification of unknown cases (Pokines 2016, 2018a). No matter how seemingly mundane, the collection of these data will allow regional patterns to emerge regarding the rate of some changes and increase our ability to estimate the PMI from these changes.

Table 21.3 Microscopic Osseous Taphonomy Checklist

Microstructure
Histological Index
Generalized destruction
Bacterial alteration
Bacterial alteration type
Fungal alteration
Fungal alteration type
Cracking
Birefringence
Thermal Alteration
Color
Color distribution in bone
Cracking (haversian canals)
Carbon deposits
Crisscross cracking
Enlarged osteocyte lacunae
Inclusion and Staining
Copper (green), iron (red), or other mineral staining
Vivianite, (framboidal) pyrite, calcite, gypsum or other crystal formation
Adipocere, other soft tissue remains
Humic acid
Soil material (sand, clay, etc.) adhering or included in pores
Plant roots (adhering/penetrating)
Fungi, bacteria (adhering, penetrating)

Recording Microscopic Taphonomic Data

To record microscopic taphonomic data (Table 21.3), a section of bone needs to be cut, and preferably a sample of long bone shaft should be used. Cancellous bone is not suited for this type of analysis, as the amount of actual bone microstructure in a section is not sufficient. A sample can be collected from bone using a Dremel® tool, hacksaw, or circular saw. If only small bone fragments are available, then these can be used in their entirety.

To preserve the features that are of interest in taphonomic studies, it is not advisable to decalcify bone as is common in fresh bone histology. In cases of very poor preservation, decalcification may result in the destruction of the sample. Many osteological laboratories will have thin-sectioning equipment for undecalcified bone available. Such facilities can include dedicated hard tissue microtomes, which cut bone, after embedding in an epoxy resin for structural reinforcement, into semi-thin sections (80–100 µm) (e.g., Van der Lubbe et al. 1988). Other methods are based on cutting slivers of bone (±300 µm), which are then mechanically ground to the desired thickness (e.g., Chinsamy and Raath 1992; Tersigni 2007). Which method is chosen depends on available technology but also on the condition of the bone; fragile, weathered bone (Chapter 11) will need to be embedded in epoxy resin (Biodur® or Buehler® for example) to help it withstand the stress of mechanical grinding and cutting. The resin needs to be fluid so it will penetrate sufficiently into the bone. Some resins produce heat during the curing process or require heat to cure, which can lead to warping or fracturing of fragile specimens (Haas and Storå 2013). Ideally, the hardness of the cured resin is comparable to that of the embedded bone, to avoid problems during sawing.

If no microtome or mechanical grinding equipment is available, Frost's rapid manual method as described by Maat et al. (2000) is a useful and affordable alternative. Briefly, a sample of bone of ±3 mm thick is cut from cortical bone; this sample is then manually ground using 220-grit abrasive paper (available in most hardware stores), with water for lubrication (Maat et al. 2000, 2001). No embedding is needed in this technique, though bone may need to be lightly stabilized using superglue (i.e., cyanoacrylate).

The finished, semi-thin sections (80–100 μm) have to be mounted on labeled glass slides to be ready for analysis. Mounting is achieved using preferably a permanent mounting medium or adhesive like Permount®, Entellan®, or Canada balsam or a rapidly curing two-component epoxy resin. The choice of mounting medium depends on the time available for this part of the process and whether the sections need to remain of good quality for only the initial analysis or will need to be used in reference collections. Cheaper and faster options like rapidly curing resin or cyanoacrylate may lead to warping of the section during mounting (Haas and Storå 2013), and these media will become opaque over time, rendering the sections unreadable.

Thin sections of bone can be analyzed using a (polarized) transmitted light microscope. Thin section samples prepared for diagenetic research can, of course, also be used for histological age determination or species identification (if taken from suitable long bones). Microscope-mounted cameras can record micrographs of the thin sections at various magnifications. Analysis can then be performed both qualitatively and quantitatively. For quantitative analysis, *ImageJ*, as mentioned above, is a widely available software that, after careful calibration, can perform various measurements such as size, area, and circularity of features. Staining of sections with histological dyes can be complicated in diagenetically altered bone, or bone that has been embedded in resin, but in some cases it may aid in visualization of features (Haas and Storå 2013).

In addition to light microscopy, high-resolution scanning electron microscopy (SEM), backscattered electron scanning microscopy (BSE-SEM), and energy dispersive x-ray spectroscopy (EDS) can be used to explore bone alteration in high resolution. These analyses are used to obtain information on the presence of different elements and mineral density (e.g., Hollund et al. 2012). Uncovered thin sections prepared for light microscopy or, preferably, the embedded bone blocks remaining after sectioning, are suitable samples for BSE-SEM, needing only some polishing to remove sawing artifacts. Thick sections of bone also can be polished to be analyzed using reflected light microscopy, a quick and affordable microscopy method (Hollund 2013). In addition, a reliable indicator specifically for biomolecular preservation can be used to expose a thick section of freshly cut bone to UV light and observe the color and intensity of its auto-fluorescence (Hoke et al. 2011).

To facilitate quantification of alteration and comparison to other possible measurements, several methods are available that are described in the Chapter 2.

Field Methods

Some taphonomic contextual data are collected in the field and, if not, are otherwise unrecoverable. These field data include the dispersal patterns of surface remains recovered in terrestrial environments and other provenience and associated artifact data. Field observations typically appear in a separate forensic recovery reports from forensic anthropological skeletal analyses. This division occurs especially in laboratories where skeletal analyses is done in the blind, i.e., temporarily restricting the information regarding the known biological profile data of the suspected identification and scene recovery context from the skeletal analyst to reduce the chance of bias in observations and conclusions (Holland et al. 2008). Blind analysis for the other aspects of the biological profile may be possible with sole practitioners, but those performing their own scene recoveries already will be aware of the taphonomic context. An exception regarding taphonomic field context is where a backlog of older cases has accumulated in storage in a medical examiner or coroner office, and these remains are sometimes lacking complete case details (Pokines 2020). These often include cases that are no longer of police interest, including cemetery, archaeological, and former anatomical teaching remains. These cold cases may include unidentified remains from recent but incompletely documented contexts. Taphonomic analysis therefore in part can reconstruct the depositional context for incomplete remains lacking full provenience information, where these data were lost or never recorded fully.

To collect field provenience data, some kind of mapping system must be in place for recording in three dimensions. These systems can be as simple as tape measure and compass systems where appropriate, and the error limits are understood and acceptable, or as complex as a total station and data logger system (Dupras et al. 2012). These also can be supplemented by the use of GPS readings for objects far away from main site clusters that cannot be mapped effectively in any other manner, with consideration for the inherent error (multiple meters) for GPS readings. Regardless of how the data are collected, they are not recoverable once the objects have been removed from their depositional context. Examination of bone dispersal patterns and distances caused by scavengers (Chapters 9 and 16), for example, will not be possible without the collection of provenience data while in the field. The articulation of individual elements also will be lost upon collection if it is not recorded and the elements are not attached by soft tissue.

The location of the site itself must be recorded in the field, and these data are normally collected at a minimum by use of a GPS reading for the site datum. It is also effective practice to mark the site datum itself in some manner, should it be necessary to return to the location for additional work. The site datum also can be triangulated to fixed objects for ease of re-location. While the locations of sites are often mostly a practical matter of logistics and jurisdiction, they also may be relevant to the identification of the remains by narrowing down the list of missing persons associated with a given area. In addition, clustering of related sites may indicate body dump behavior of the individuals responsible for the deaths (Chapter 10). Patterns of site location data also may be useful for analysis of broader taphonomic trends, including the rate at which various postmortem processes (including animal scavenging and subaerial bone weathering) proceed in different types of environment (forest, wetlands, agricultural fields, urban parks, etc.). These data for a particular environment may inform future estimations of PMI through higher-order taphonomic analyses of regional and seasonal patterns.

Other field data to be collected at the time of recovery include the context of remains relative to their physical environment. For example, whether plants had begun to grow over or through remains or leaf litter had accumulated on top of them are relevant data regarding estimation of the PMI, at least in terms of minimum spring/summer or fall/winter seasons that have passed since deposition. Where more time has passed, the growth rings from tree roots (dendrochronology) may be useful in providing a minimum age for the site (Pokines 2018b; Willey and Heilman 1987). The necessary root samples must be collected and documented in the field, including their location relative to a burial such that the burial could not have been excavated with the root already in place. The later laboratory findings of a tree root's age would not be usable without the field data relating the growth of that root relative to a set of remains. Other types of field data relevant to the taphonomic context include the relative density of human population in the area, signs of animal activity (droppings, fur, footprints, etc.) on a scene that may relate to tooth marks on bones, the density and species of tree canopy and understory above a site, any meteorological effects (e.g., recent heavy rains) that may have affected the state of the remains upon collection, and the land-use history of an area (former agricultural or logging activity, previous soil disturbance, etc.) prior to the deposition of the remains.

For estimations of the PMI based upon decomposition scoring methods (Megyesi et al. 2005; Moffatt et al. 2016; van Daalen et al. 2017), data regarding atmospheric and water temperature are required. Since the location of a body within a jurisdiction cannot be predicted in advance, forensic anthropologists cannot collect these data themselves except under experimental or serendipitous conditions. Weather data normally are collected from weather stations, and the data for these are available for free download from the National Oceanographic and Atmospheric Administration (NOAA 2021). It is recommended that these data be stored in a spreadsheet for a given forensic case so that the estimations of PMI calculated from them can be reviewed later.

Report Writing

Taphonomic effects to the bones also record data for PMI estimation. These include the general state of the bones, whether they are still greasy, only retain organic sheen, or have degraded to a chalkier appearance through the loss of organic content. The state of the bones, even if it cannot supply a numerical estimate of the PMI, can help indicate the general provenience of the bones and thus their general time period, such as recent, cemetery, or archaeological (Chapter 5). Subaerial weathering of the bones and the progression of cracking and surface loss can give numerical estimates of the PMI in years (Behrensmeyer 1978). There is much known variation based upon climate and microenvironment (Chapter 11), so direct application of Behrensmeyer's (1978) PMI estimates (based upon large nonhuman vertebrates in a savanna environment in Kenya) should not be uncritically applied to random environments yielding human remains. Advanced subaerial weathering in any environment, however, normally takes years to develop, so descriptions of weathering effects for general skeletal taphonomic description also overlap with the data used to estimate PMI.

Combining the taphonomic observations section with PMI estimation yields a more logical and efficient forensic anthropology report, since the source of most PMI data that can be derived from a set of remains are taphonomic (Chapter 1). At the earlier end of the time scale these include scoring of the decomposition stage of different body areas in order to estimate the PMI from the Accumulated Degree-Days necessary to reach that state (Megyesi et al. 2005; Moffatt et al. 2016; van Daalen et al. 2017; Chapter 3). Since these data also provide an overall description of the state of soft tissue, including its locations, quantity, degree of desiccation, color change, and adipocere formation, they serve a dual purpose. Descriptions of taphonomic effects should be clear, include appropriate citations detailing exactly those effects, and include photographic images referenced within the text. Ordering of descriptions generally proceed best by similar types of effects, such as general preservation of bone, staining of all types, other environmental effects including subaerial weathering, and alterations by consuming or colonizing taxa. Any observations regarding the relative timing of taphonomic effects also can be included, especially where these are relevant to explaining the postmortem history of a scene. Bone dispersal, for example, is often accompanied by evidence of scavenger gnawing, and the data from both of these sources reinforce the other. The overall set of observations often will indicate which taphonomic environment is consistent with their origin, including ritual use, former cemetery burial, surface exposure, or marine immersion (Pokines 2018a; Chapter 1). Since the decision to rule out remains as being of further police interest is often based upon these observations, the report must document which observations were used to make the final decision regarding their ultimate disposition, including turnover to another agency.

Graduate Education in Osseous Taphonomy

The authors recommend that all graduate training programs in forensic anthropology include significant course work and when possible supervised case work in taphonomy. Apart from the obvious necessity for ongoing case resolution, this topic receives significant coverage on the Board Examination administered by the American Board of Forensic Anthropology (ABFA 2021). Its component contribution to the examination content, both written and practical, has expanded over time and may expand in the future, including the related topic of PMI estimation (Bartelink et al. 2020; Boyd et al. 2020). Importantly, application to the ABFA Board examination requires the submission of multiple case reports that are expected to address the taphonomic analysis of the remains and PMI estimation. The bench notes for these cases also are submitted for review for examination eligibility (ABFA 2021), so the preparation and use of taphonomic checklists and scoring methods can aid greatly in the ordering, completeness, and presentation of this information.

Taphonomic experiments in the field and laboratory are also highly amenable to M.A./M.S. thesis or Ph.D. dissertation projects. Some of these can be performed with minimal funding, although secured, undisturbed outdoor research areas are required to study decomposition (Jantz and Jantz 2008), and the permission process to use human remains is extensive. Other projects require areas with partially restricted or unrestricted access to remains to correspond more closely to the combined taphonomic processes common to that environment, especially where natural scavenger behavior is being studied (Chapters 9 and 16). Many of these experiments use nonhuman remains as a proxy for human, especially domesticated pig (*Sus scrofa*), due to similarities in diet and anatomical, physiological, and immunological systems with human (Meurens et al. 2012; Summerfield et al. 2015). Using full adult (fused) pig remains is sometimes cost-prohibitive, and individuals at slaughtering age are typically juvenile (Zeder et al. 2015), with the cost for pigs increasing greatly among larger sizes approaching adult human. Stillborn pig remains are also a cost-effective model for human perinatal remains. Pig decomposition, however, has been found to differ from that of human remains in the same environment (DeBruyn et al. 2021; Matuszewski et al. 2020), so modifications to decomposition scoring scales may be necessary (Keough et al. 2017). White-tailed deer (*Odocoileus virginianus*) is also an acceptable substitute in some applications, especially where isolated bones are needed. This species is sometimes preferable to pig, as adult (fused) deer bones can be obtained inexpensively during the local hunting season from butchers who process wild game. Deer bones also bear morphological and structural similarities to human bones (Kieser et al. 2014; Kumar et al. 2000). For whole body studies, pigs are preferable to deer, due to pig soft tissue similarities to humans. Butchered pig heads are generated in large amounts from commercial operations and can be obtained inexpensively, although it is standard to have the eyes and tongue already removed, and trauma from the killing bolt on the frontal. Isolated pig heads may be useful in studies requiring large samples with soft tissue, including most skin, intact.

Some taphonomic experiments require a time commitment beyond the normal limits available for thesis work, so professional researchers are also needed to address some questions, including the effects of long-term burial (Armour-Chelu and Andrews 1996) or surface exposure (Pokines and Ames 2015). Some long-term thesis projects, however, are a necessity and can yield substantial results where years of data collection are required, for projects such as the long-distance transport of bones in riverine systems (Evans 2015). A further option is for multi-stage projects involving a succession of students all monitoring the same long-term project under constant faculty supervision. With the large amount and diversity of taphonomic experiments that are ongoing or have concluded, there is, in theory, a large amount of bone already available for histological studies. Only small samples of an individual bone are required and can be taken without significant damage. Recording histological diagenetic features from remains with a fully known taphonomic history is invaluable to help reconstruct taphonomic histories from bones lacking these data. Ideally, however, experiments can be devised to address diagenetic research questions, where histology can be the focus or part of the suite of techniques employed to document various aspects of taphonomic change.

All human osteology graduate students and related careers already have extensive experience with anatomical teaching specimens (Pokines et al. 2017), so they bring their own experience to the taphonomic analysis of cases of this type. They may not, however, have prior experience with the many ways in which such remains can get repurposed for ritual or display (Chapter 8). Effective teaching collections for much taphonomy training can be built from discarded nonhuman cases that underwent the same patterns of effects in the same environments, including burial, terrestrial, and marine (Pokines 2015, 2016, 2020). Instructors can make additional collections of nonhuman remains to illustrate taphonomic effects that are rarer within their jurisdiction. Not all effects upon human remains, however, will have exact parallels in nonhuman remains. In particular, former cemetery remains (Chapter 5) will not have a nonhuman counterpart available that has undergone the same processes of long-term burial. Training on these types of remains and others that do not have a viable nonhuman substitute, including trophy skulls and ritual remains, can take place through internships and workshops in medical examiner/coroner offices and in the case of cemetery/archaeological remains, with State archaeological agencies. As with any aspect of forensic anthropological reports, taphonomic sections may come under peer review (Holland et al. 2008), so all practitioners operating in the same laboratory must be trained in taphonomy also to verify the observations, conclusions, and reporting of others.

While graduate education in taphonomy must be geared toward the practicalities of forensic case analysis, it also must include a thorough foundation in taphonomic theory, history, and applications in sister disciplines including especially paleontology and archaeology, from which much academic taphonomy derives and overlaps with experimentally (Chapter 1). Related studies include ethology, natural history, and ecology, as the behavior of scavenging species is often key to understanding the chain of postmortem events that affected a set of human remains. This includes the study of bioerosion in bone which can be linked to studies on the microbiome of death, which is a promising field in forensics (Metcalf 2019). Taphonomic education and research also invite collaboration with specialists in other disciplines, including chemistry, microbiology, botany, and oceanography. Forensic taphonomy is an ever-expanding field, and education in this topic should be geared toward a greater inclusiveness of the relationships between the remains and all natural processes and taxa as the former proceed from the biosphere to the lithosphere.

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References

Allison, P. A., and D. E. G. Briggs (eds.) (1991) *Taphonomy: Releasing the Data Locked in the Fossil Record*. Springer, Dordrecht.

American Board of Forensic Anthropology (ABFA) (2021) Application to sit for the certification examination in forensic anthropology. Electronic document, http://theabfa.org/faq/applicants/, accessed 21 January 2021.

Armour-Chelu, M., and P. Andrews (1996) Surface modification of bone from Overton Down, Wiltshire. In *The Experimental Earthwork Project 1960–1992* ed. by M. Bell, P. J. Fowler, and S. W. Hillson, pp. 178–185. Council for British Archaeology, York, UK.

Bartelink, E. J., D. C. Boyd, D. L. France, J. T. Pokines, and D. Prince-Zinni (2020) The American Board of Forensic Anthropology turns 40: Historical perspectives and current trends in certification for forensic anthropology. *Forensic Anthropology* 3(2):102–110.

Behrensmeyer, A. K. (1978) Taphonomic and ecologic information from bone weathering. *Palaeobiology* 4(2):150–162.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1991) Recognition of cemetery remains in the forensic setting. *Journal of Forensic Sciences* 36(1):230–237.

Berryman, H. E., W. M. Bass, S. A. Symes, and O. C. Smith (1997) Recognition of cemetery remains in the forensic setting. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 165–170. CRC Press, Boca Raton, FL.

Bonnichsen, R., and M. H. Sorg (eds.) (1989) *Bone Modification*. Center for the Study of the First Americans, Orono, ME.

Boyd, D. C., E. J. Bartelink, N. V. Passalacqua J. T. Pokines, and M. A. Tersigni-Tarrant (2020) The American Board of Forensic Anthropology's certification program. *Forensic Anthropology* 3(2):112–119.

Buikstra, J. E., and D. H. Ubelaker (eds.) (1994) *Standards for Data Collection from Human Skeletal Remains*. Arkansas Archeological Survey Research Series No. 44, Fayetteville, AR.

Chinsamy, A., and M. A. Raath (1992) Preparation of fossil bone for histological examination. *Paleontology of Africa* 29:39–44.

DeBruyn, J. M., K. M. Hoeland, L. S. Taylor, J. D. Stevens, M. A. Moats, S. Bandopadhyay, S. P. Dearth, H. F. Castro, K. K. Hewitt, S. R. Campagna, A. M. Dautartas, G. M. Vidoli, A. Z. Mundorff, and D. W. Steadman (2021) Comparative decomposition of humans and pigs: Soil biogeochemistry, microbial activity and metabolomic profiles. *Frontiers in Microbiology* 11:608856. DOI: 10.3389/fmicb.2020.608856.

Denys, C., and M. Patou-Mathis (eds.) (2014) *Manuel de Taphonomie*. Errances, Arles, France.

Dirkmaat, D. C., and L. L. Cabo (2016) Forensic archaeology and forensic taphonomy: Basic considerations on how to properly process and interpret the outdoor forensic scene. *Academic Forensic Pathology* 6(3):439–454.

Donovan, S. K. (ed.) (1994) *The Palaeobiology of Trace Fossils*. Wiley, Chichester, UK.

Duhig, C. (2003) Non-forensic remains: The use of forensic archaeology, anthropology and burial taphonomy. *Science and Justice* 43(4):211–214.

Dupras, T. L., J. J. Schultz, S. M. Wheeler, and L. J. Williams (2012) *Forensic Recovery of Human Remains: Archaeological Approaches* (2nd ed.). CRC Press, Boca Raton, FL.

Evans, T. (2015) *A Critical Evaluation of Our Understanding of Bone Transport and Deposition in Fluvial Channels*. Ph.D. Dissertation, Montana State University, Bozeman, MT.

Fernández-Jalvo, Y., and P. Andrews (2016) *Atlas of Taphonomic Identifications: 1001+ Images of Fossil and Recent Mammal Bone Modification*. Springer, Dordrecht.

Fisher (1995) Bone surface modifications in zooarchaeology. *Journal of Archaeological Method and Theory* 2(1):7–68.

Haas, K., and J. Storå (2013) Different preparation techniques—Similar results? On the quality of thin-ground sections of archaeological bone. *International Journal of Osteoarchaeology* 25(6):935–945.

Haglund, W. D., and M. H. Sorg (eds.) (1997) *Forensic Taphonomy: The Postmortem Fate of Human Remains*. CRC Press, Boca Raton, FL.

Haglund, W. D., and M. H. Sorg (eds.) (2002) *Advances in Forensic Taphonomy: Method, Theory, and Archaeological Perspectives*. CRC Press, Boca Raton, FL.

Hoke, N. J., J. Burger, C. Weber, N. Benecke, G. Grupe, and M. Harbeck (2011) Estimating the chance of success of archaeometric analyses of bone: UV-induced bone fluorescence compared to histological screening. *Palaeogeography, Palaeoclimatology, Palaeoecology* 310:23–31.

Holland, T., J. Byrd, and V. Sava (2008) Joint POW/MIA Accounting Command's Central Identification Laboratory. In *The Forensic Anthropology Laboratory* ed. by M. W. Warren, H. A. Walsh-Haney, and L. E. Freas, pp. 47–63. CRC Press, Boca Raton, FL.

Hollund, H. I., M. M. E. Jans, M. J. Collins, H. Kars, I. Joosten, and S. M. Kars (2012) What happened here? Bone histology as a tool in decoding the post-mortem histories of archaeological bone from Castricum, the Netherlands. *International Journal of Osteoarchaeology* 22(5):537–548.

Hollund, H. I. (2013) Diagenetic screening of bone samples: Tools to aid taphonomic and archaeometric investigations. *Geoarchaeological and Bioarchaeological Studies* 15. VU University, Amsterdam.

Jantz, L. M., and R. L. Jantz (2008) The Anthropology Research Facility: The outdoor laboratory of the Forensic Anthropology Center, University of Tennessee. In *The Forensic Anthropology Laboratory* ed. by M. W. Warren, H. A. Walsh-Haney, and L. E. Freas, pp. 195–212. CRC Press, Boca Raton, FL.

Keough, N., J. Myburgh, and M. Steyn (2017) Scoring of decomposition: A proposed amendment to the method when using a pig model for human studies. *Journal of Forensic Sciences* 62(4):986–993.

Kieser, D. C., S. Kanade, N. J. Waddell, J. A. Kieser, J.-C. Theis, and M. V. Swain (2014) The deer femur—A morphological and biomechanical animal model of the human femur. *Bio-Medical Materials and Engineering* 24(4):1693–1703.

Kumar, N., S. Kukreti, M. Ishaque, and R. Mulholland (2000) Anatomy of deer spine and its comparison to the human spine. *The Anatomical Record* 260(2):189–203.

Lyman, R. L. (1994) *Vertebrate Taphonomy*. Cambridge University Press, Cambridge.

Maat, G. J. R., R. P. M. Van den Bos, and M. J. Aarents (2000) Manual for the preparation of ground sections for the microscopy of bone tissue. *Barge's Anthropologica*. Leiden University Medical Centre, Leiden, the Netherlands.

Maat, G. J. R., R. P. M. Van Den Bos, and M. J. Aarents (2001) Manual preparation of ground sections for the microscopy of bone tissue: Update and modification of Frost's 'rapid manual method'. *International Journal of Osteoarchaeology* 11(5):366–374.

Martin, R. E. (1999) *Taphonomy: A Process Approach*. Cambridge University Press, Cambridge, UK.

Matuszewski, S., M. J. R. Hall, G. Moreau, K. G. Schoenly, A. M. Tarone, and M. H. Villet (2020) Pigs vs people: The use of pigs as analogues for humans in forensic entomology and taphonomy research. *International Journal of Legal Medicine* 134(1–2):793–810.

Megyesi, M. S., S. P. Nawrocki, and N. H. Haskell (2005) Using Accumulated Degree-Days to estimate the postmortem interval from decomposed human remains. *Journal of Forensic Sciences* 50(3):618–626.

Metcalf, J. L. (2019) Estimating the postmortem interval using microbes: Knowledge gaps and a path to technology adoption. *Forensic Science International: Genetics* 38:211–218.

Meurens, F., A. Summerfield, H. Nauwynck, L. Saif, and V. Gerdts (2012) The pig: A model for human infectious diseases. *Trends in Microbiology* 20:50–57.

Micozzi, M. S. (1991) *Postmortem Change in Human and Animal Remains: A Systematic Approach*. Charles C Thomas, Springfield, IL.

Miller, G. J. (1969) A study of cuts, grooves, and other marks on recent and fossil bones. 1. Animal tooth marks. *Tebiwa* 12:9–19.

Miller, G. J. (1975) A study of cuts, grooves, and other marks on recent and fossil bones. 2. Weathering cracks, fractures, splinters, and other similar natural phenomena. In *Lithic Technology: Making and Using Stone Tools* ed. by E. H. Swanson, Jr., pp. 211–226. Aldine, Chicago.

Moffatt, C., T. Simmons, and J. Lynch-Aird (2016) An improved equation for TBS and ADD: Establishing a reliable postmortem interval framework for casework and experimental studies. *Journal of Forensic Sciences* 61(S1):S201–S207.

Morlan, R. E. (1984) Toward the definition of criteria for the recognition of artificial bone alterations. *Quaternary Research* 22(2):160–171.

National Oceanographic and Atmospheric Administration (NOAA) (2021) Data Tools: Local Climatological Data (LCD). Electronic document, https://www.ncdc.noaa.gov/cdo-web/datatools/lcd, accessed 7 February 2021.

Nawrocki, S. P. (1995) Taphonomic processes in historic cemeteries. In *Bodies of Evidence: Reconstructing History through Skeletal Analysis* ed. by A. Grauer, pp. 49–66. Wiley-Liss, New York.

Pokines, J. T. (2015) Identification of nonhuman remains received in a medical examiner setting. *Journal of Forensic Identification* 65(3):223–246.

Pokines, J. T. (2016) Taphonomic alterations to terrestrial surface-deposited human osseous remains in a New England environment. *Journal of Forensic Identification* 66(1):59–78.

Pokines, J. T. (2018a) Differential diagnosis of the taphonomic histories of common types of forensic osseous remains. *Journal of Forensic Identification* 68(1):87–145.

Pokines, J. T. (2018b) Two cases of dendrochronology used to corroborate a forensic postmortem interval. *Journal of Forensic Identification* 68(4):457–465.

Pokines, J. T. (2020) The case of the… cases: The flow of the ordinary into a medical examiner's office. In *Case Studies in Forensic Anthropology: Bonified Skeletons* ed. by H. Garvin and N. R. Langley, pp. 291–302. CRC Press, Boca Raton, FL.

Pokines, J. T. (2021) Laws of taphonomic relative timing and their application to forensic contexts. *Forensic Anthropology* 4(1):1–14.

Pokines, J. T., and C. J. H. Ames (2015) Weathering and dispersal of a cattle (*Bos taurus*) carcass in the desert of eastern Jordan over a six-year interval. *Journal of Taphonomy* 13(1):17–31.

Pokines, J. T., N. Appel, C. Pollock, C. J. Eck, A. G. Maki, A. S. Joseph, L. Cadwell, and C. D. Young (2017) Anatomical taphonomy at the source: Alterations to a sample of 84 teaching skulls at a medical school. *Journal of Forensic Identification* 67(4):600–632.

Rogers, T. L. (2005) Recognition of cemetery remains in a forensic context. *Journal of Forensic Sciences* 50:5–11.

Schultz, J., M. Williamson, S. P. Nawrocki, A. Falsetti, and M. Warren (2003) A taphonomic profile to aid in the recognition of human remains from historic and/or cemetery contexts. *Florida Anthropologist* 56(2):141–147.

Shipman, P. (1981) *Life History of a Fossil: An Introduction to Taphonomy and Paleoecology*. Harvard University Press, Cambridge, MA.

Summerfield, A., F. Meurens, and M. E. Ricklin (2015) The immunology of the porcine skin and its value as a model for human skin. *Molecular Immunology* 66(1):14–21.

SWGANTH (2013) Taphonomic observations in the postmortem interval. Electronic document, https://www.nist.gov/system/files/documents/2018/03/13/swganth_taphonomic_observations.pdf, accessed 23 April 2021.

Tersigni, M. A. (2007) Frozen human bone: A microscopic investigation. *Journal of Forensic Sciences* 52(1):16–20.

Ubelaker, D. H. (1997) Taphonomic applications in forensic anthropology. In *Forensic Taphonomy: The Postmortem Fate of Human Remains* ed. by W. D. Haglund and M. H. Sorg, pp. 77–90. CRC Press, Boca Raton, FL.

van Daalen, M. A., D. S. de Kat, B. F. L. Oude Grotebevelsborg, R. de Leeuwe, J. Warnaar, R. J. Oostra, and W. L. J. M. Duijst-Heesters (2017) An aquatic decomposition scoring method to potentially predict the postmortem submersion interval of bodies recovered from the North Sea. *Journal of Forensic Sciences* 62(2):369–373.

Van Der Lubbe, H. B. M., C. P. A. T. Klein, and K. De Groot (1988) A simple method for preparing thin (10 µm) histological sections of undecalcified plastic embedded bone with implants. *Stain Technology* 63(3):171–176.

Walsh-Haney, H. A., M. W. Warren, and L. E. Freas (2008) The working forensic anthropology laboratory. In *The Forensic Anthropology Laboratory* ed. by M. W. Warren, H. A. Walsh-Haney, and L. E. Freas, pp. 7–21. CRC Press, Boca Raton, FL.

Wedel, V. L., and A. Galloway, eds. (2014) *Broken Bones: Anthropological Analysis of Blunt Force Trauma* (2nd ed.). Charles C Thomas, Springfield, IL.

Willey, P., and A. Heilman (1987) Estimating time since death using plant roots and stems. *Journal of Forensic Sciences* 32(5):1264–1270.

Zeder, M. A., X. Lemoine, and S. Payne (2015) A new system for computing long-bone fusion age profiles in *Sus scrofa*. *Journal of Archaeological Science* 55:135–150.

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