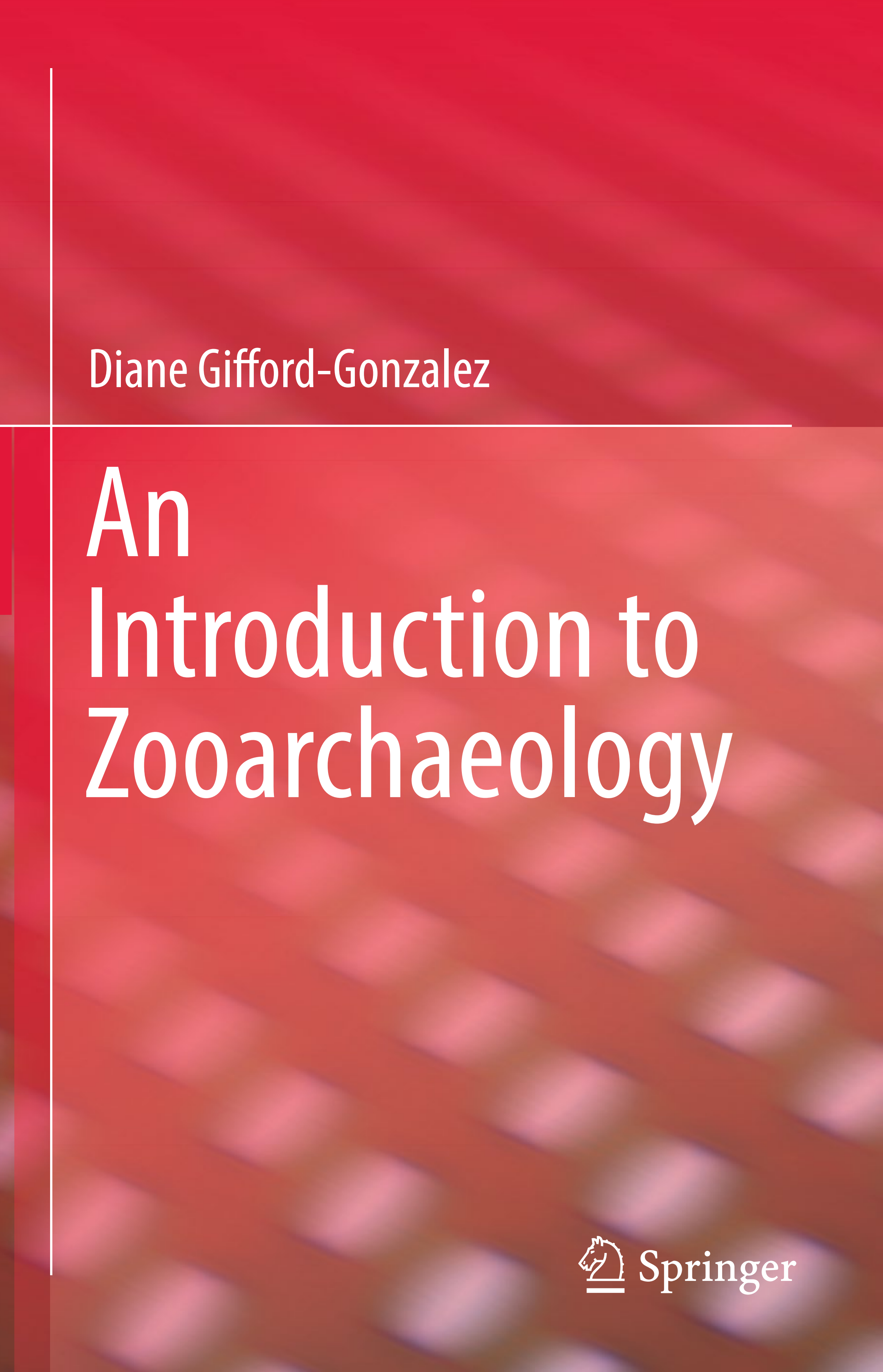

Diane Gifford-Gonzalez

An Introduction to Zooarchaeology

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To the Memory of My Parents
Gloria María González
John Patric Gifford

Acknowledgments

One gratifying aspect of a life working in a relatively new field has been the mutual support that most colleagues have sustained with one another. Like other pioneers, most of us have found it more beneficial to share and occasionally work in teams than to hole up our own private forts, protecting our ideas and data. Sometimes gunplay broke out on the frontier, but a remarkable ability to not let intellectual differences ruin personal friendships has generally prevailed. I would not be writing this book were it not for a long history of influential conversations, arguments, inspirations, and advice from colleagues and former graduate students in the field. Beyond these have been shared reprints (when those were still fashionable), data, comments, unpublished texts, bibliographic citations, jokes, and basic human kindnesses offered by many colleagues. I want to specially acknowledge María Clara Álvarez, Kay Behrensmeyer, Juan Bautista Belardi, Lew Binford, Rob Blumenschine, Cristie Boone, Florencia Borella, Luís Borrero, Joanne Bowen, Cheryl Claassen, Dinah Crader, María Cruz, Jon Driver, Rob Gargett, Don Grayson, Bryan Scott Hockett, Vicky Horwitz, Dave Huelsbeck, Anneke Janzen, Richard Klein, Karen Lupo, Lee Lyman, Fiona Marshall, Arek Marciniak, Curtis Marean, Jorge Martínez Moreno, Bernard Mbae, Willy Mengoni Goñalons, Francisco Mena Larraín, Mariana Mondini, Sebastian Muñoz, James O'Connell, Sandra Olsen, Sebastian Payne, Anne Pike-Tay, Dave Schmitt, Mary Stiner, Charlotte Sunseri, Jun Sunseri, Paola Villa, Gao Xing, and Tim White. I deeply thank my Argentine colleagues for their hospitality and their example of persisting as scholars through times of adversity.

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for his advice, and the final product has benefited greatly from his advice. I alone am responsible for the errors and opinions of this work.

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About the Author

Diane Gifford-Gonzalez is among the first cohort of archaeologists trained in faunal analysis and has authored numerous publications, including some cited as major formulations of zooarchaeological theory and method. She takes an international perspective, having researched in Africa and western North America and offered advanced seminars and workshops in the USA, Argentina, China, Kenya, Norway, and Spain. She is an elected member of the Committee of Honor, International Council Conference for Archaeozoology (ICAZ).

Part I
An Orientation to Zooarchaeology

Chapter 1
Introduction

In 1950, there were few, if any, zooarchaeologists. Today the number of zooarchaeologists in North America is growing toward equal proportions with those specializing in the more traditional fields of lithic and ceramic analysis (Zeder 1997). In earlier days, archaeologists sent the more complete bones and shells from their sites to zoologists or paleontologists who provided a list of species present. Lyman (2016a) reports that over 78% of North American reports on archaeofaunas published between 1900 and 1944 fell into this category. Faunal reports were usually in monographs' appendices, listing taxonomic groups, sometimes with "rare," "common," or other quantitative estimates noted. In the 1960s and early 1970s several visionary paleontologists and zoologists began training young archaeologists in taxonomy and anatomical identification. Today, zooarchaeology is a self-reproducing field taught in many university departments of anthropology or archaeology. As archaeologists have literally taken faunal analysis into their own hands, they have debated how best to use animal remains to study everything from early hominin hunting or scavenging to animal production in ancient market economies.

1.1 The Relevance of Archaeofaunal Remains

The term "zooarchaeology" (Olsen 1971) aptly describes faunal analysis aimed at addressing archaeological questions. Archaeological study of animal remains naturally requires knowledge drawn from zoology and paleontology, but reading them for evidence of past human behavior calls for a unique combination of supplemental strategies. Like its parallel field of study, paleoethnobotany (Pearsall 1989; Piperno 1988), archaeological faunal analysis combines natural historic methods with approaches drawn from archaeology, anthropology, and other social sciences. Zooarchaeologists today research a great range of topics, including whether slaves in the antebellum American South provisioned themselves from the countryside,

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how cities of ancient Mesopotamia were supplied with animal food, and whether Neanderthals foraged similarly to anatomically modern humans.

The zooarchaeological literature is growing so swiftly that even specialists have difficulty keeping pace. Some impetus for this explosion in zooarchaeological research arose from application of new technologies to faunal research. Starting in the 1970s, stable isotope analyses of human bones were used to reconstruct diet (van der Merwe and Vogel 1978). More recently, stable isotope analyses have been applied to animal remains to explore herd management, seasonality, climate, biogeography, and paleoecology (see Chap. 20). Application of scanning electron microscopy (SEM) in the 1980s greatly facilitated definition of "signatures" of non-human and human bone modifiers (Potts and Shipman 1981). However, key developments in zooarchaeology often arose from novel perspectives on the basic evidence and from new assertions that zooarchaeological analysis could testify to aspects of human behavior previously deemed inaccessible, such as hominin foraging strategies.

1.2 This Book's Focus and Orientation

Animal remains from archaeological sites have been used to infer three kinds of information: the age of deposits (chronology); paleoenvironment and paleoecological relations among humans and other species; human choices and actions related to use of animals as food and raw materials. Methods for reconstructing human diet and behavior have undergone the greatest growth over the last four decades, and most of this book addresses the second and third areas.

This book deals with what I know best: vertebrate zooarchaeology, and within that, analysis of mammalian bones and teeth. A literature on identification and analysis of fish from archaeological sites exists (Brinkhuizen and Clason 1986; Casteel 1976; Wheeler and Jones 1989), as does that for birds (Carey 1982; Dawson 1969; Howard 1929; Gilbert et al. 1985). An online resource for North American bird bones is found at the Royal British Columbia Museum's "Avian Osteology" web pages http://www.royalbcmuseum.bc.ca/Natural_History/Bones/homepage.htm. Cheryl Claassen's work (1998) on analysis of molluscan remains offers a fine theoretical overview.

The text's main focus is archaeological faunal analysis as practiced in Canada and the United States, with some attention to its practice in Britain and other parts of the English-speaking world. This linguistic grouping forms a logical unit, not only because of ease of communication in a common language but also because of the degree of shared perspectives on archaeology. However, from my own experience as a non-Americanist researching and teaching overseas, I am aware of the productive work of and linkages among zooarchaeologists in the Americas and their counterparts in Europe, Africa, and Asia, and these will also be mentioned as relevant.

This text is not a guide to identification. Many visual guides to faunal identification exist, and notable examples will be cited in Chap. 6. Neither is this book a "how-to" manual, with instructions for zooarchaeological analysis. Instead, it reviews the considerations that underlie decisions about identifying, recording, and quantifying zooarchaeological data. Most of us understand that no two sites are alike and that an irredeemable loss of data can result from digging according to a rote formula rather than with thought to their sites' special aspects. So, too, no two faunal assemblages are identical, nor are conditions under which a zooarchaeologist must analyze a given sample. My intention here is to encourage readers to develop their own knowledge bases that allow them to formulate a systematic and appropriate research plan.

Moreover, zooarchaeology is in a state of swift theoretical and methodological development. Specific current issues discussed in this book may be modified substantially in light of new research within only a few years of its publication. I therefore believe it more useful to review broader factors that must be taken into account at various stages of analysis rather than pushing my own or anyone else's detailed agenda. We do need greater standardization of data classes and scrupulous attention to conservation and documentation, but optimal research design requires a flexibility that no one-size-fits-all approach can offer. If pressed for the absolutely proper way to practice zooarchaeological analysis, I'd say, "thoughtfully."

Persons familiar with the zooarchaeological literature may ask how this book differs from my friend and colleague R. Lee Lyman's (1994) *Vertebrate Taphonomy*. This is especially a fair question because Lyman and I have generally similar methodological perspectives. I believe the difference between our books is not orientation but focus. I agree with Lyman (1994:33) that hominin modifications of animal remains fall under the larger rubric of taphonomic effects and that there is no *a priori* reason to set human effects apart from those of other agents that can leave their marks on bone, shell, or other organic remains. My book narrows the focus from taphonomy as a whole to the practice of zooarchaeology, because most archaeologists, including those who work with animal remains, ultimately want to study human behavior and its contexts. From this perspective, the main questions addressed in the present book are: what can animal remains from archaeological contexts tell us about the people who handled them, in what kinds of environmental context did they act, and what was the nature of interactions between humans and animals?

However, this book does not ignore the effects of nonhuman actors because zooarchaeological analysis must distinguish such evidence from that which reflects human activities. The need to specify effects of non-human processes on a sample does not stem from the aim to correct for their effects or to "un-bias" a sample. Chapter 3 explains why I believe this is an unrealistic goal. Rather, it stems from the view that all evidence of pre- and post-mortem agency in archaeological faunal samples tells us something that is relevant to the lived human past. A substantial part of this book will address recognizing the traces of the action of non-human bone-modifiers and the implications of their effects for zooarchaeological analysis.

Likewise, it is fair to ask how this book differs from *Zooarchaeology*, by my colleagues Betsy Reitz and Elizabeth Wing (2008). That book, like this one, focuses on humans and their interactions with animals, as testified to by zooarchaeological materials. My own approach overlaps considerably with that of Reitz and Wing because we consider similar research problems using similar methods and techniques. This book devotes much less time to invertebrates, relatively less to laying out ecological theory and basic comparative anatomy, and relatively more to presenting an epistemological framework in which to place and coordinate zooarchaeological knowledge and practice. As well, this book provides more detailed information on bone surface modifications and debates over the meanings of element frequencies. I believe that our respective books are thus largely complementary.

In much these same ways, this book differs from Nerissa Russell's (2012) *Social Zooarchaeology* in its presentation of a conceptual framework for producing and integrating zooarchaeological knowledge, emphasis on documenting bone modifications, and relatively less stress on applications of zooarchaeology to explore social relationships. In fact, my own inclinations have always been toward this goal, and I endorse Russell's approach.

This is a methodologically focused book. It discusses the logic of zooarchaeological method, including uniformitarianism, the potential and limits of analogy, as well as how one's analytic categories, sorting choices, quantification and statistical analysis, and other analytic decisions can ultimately affect one's inferences. However, methods come into being within theoretical perspectives, explicit or implicit, and this text will also explore theoretical perspectives that stand behind the methods examined. Given this, one may well ask from what theoretical position I have written a methodologically focused book. The answer to that question is twofold. One relates to my general view of theory, and the other relates to specific theoretical viewpoints I bring to my own research in zooarchaeology.

Much of my own published work could be classed as "methodological" rather than "theoretical," according to the view that archaeological theory can be divided into distinct realms of "high" or general theory, middle-range or interpretive theory, methods, and techniques. I have devoted much of my career examining how archaeological reasoning, analogy, and "uniformitarian" assumptions work themselves out in zooarchaeology in terms of assigning meaning to archaeological materials (epistemology) and of inference. The latter is what David Clarke (1973) called "archaeological metaphysics," that is, how archaeologists reason, why we feel that certain steps in reasoning are sound, why and how some interpretations or scenarios seem more plausible than others, and how we check ourselves. According to the classification outlined above, these are methodological concerns, yet they are intimately involved with linking data to general theory and to how we construct plausible arguments. Such metaphysical issues, I believe, underlie several debates in the last 30 years' zooarchaeological literature. Chapter 3 of this book explores this area in more detail.

But if we accept that all method is theoretically informed, what kind of knowledge is zooarchaeology? After only a little reflection, it is apparent that some archaeological knowledge is cumulative and enduring, despite major paradigmatic shifts in "general theory." Such enduring understandings involve both theory and method, and they are so fundamental that we archaeologists usually do not consider their unique qualities. The principles and practices of stratigraphic analysis, passed down to us from sixteenth-century antiquarians and eighteenth-century field geologists, are lasting components of archaeological concepts and practice. These abiding fields of archaeological knowledge are largely based in consistent relations between cause and effect. In this, they link to other areas of scientific research that continue to contribute new and useful refinements to archaeology, as in the case of accelerator mass spectrometry (AMS) versus conventional radiocarbon dating. They build upon earlier understandings of the world in logical ways, and they are cornerstones of archaeological reasoning. Both stratigraphy and radiocarbon dating aid the temporal ordering of objects and sites, a fundamental archaeological operation. They have carried on from one archaeological paradigm to another and are accepted as valid and used by people with quite disparate theoretical agendas. For example, archaeologists with divergent theoretical commitments may debate the social and ideological roles that Stonehenge played for ancient peoples, but all will incorporate stratigraphic reasoning and radiocarbon dates in their arguments.

As a field of systematic knowledge, zooarchaeology is not yet on equal footing with stratigraphy and radiometric dating. However, I believe it is similar in nature to them and is in the process of developing into a parallel body of theory, method, and practice. Like them, it focuses on materials with properties that are uniform over the time and space we study as archaeologists. These properties govern how humans, animals, plants, and geological processes interact with animal bodies and how those interactions produce the traces we study. Zooarchaeology has continual and fruitful interactions with anatomy, physiology, zoology, veterinary and nutritional science, ecology, paleontology, and geochemistry for information on "source side" (Wylie 2002) processes and their outcomes.

Given this view of zooarchaeology as an emerging field of theory and practice, my goal in this book is to outline some of its fundamental and logically connected building blocks. I thus hope the book will, like a handbook on stratigraphic documentation and analysis, prove useful to students and researchers investigating a variety of cases from a range of theoretical perspectives.

It is fair to ask what "general theory" (Binford 1978) I mobilize in my own zooarchaeological research. I have been working with archaeofaunas from African sites yielding pastoral livestock for about 40 years (Gifford et al. 1980; Gifford-Gonzalez 1998, 2000, 2004). I have also spent time with contemporary pastoralists and read widely about pastoral adaptations. This literature is written from a variety of theoretical perspectives that I have assessed for their usefulness and fit with the way I suspect the world works. I have also read ecology and evolutionary biology. My questions include: how different were these earliest owners of pastoral livestock from ethnographically documented groups in their mix of species herded, mobility, age-specific slaughtering practices, consumption, and refuse disposal practices? How diverse were they in all these, from central Kenya to Tanzania's Serengeti Plains? Do any of these zooarchaeologically investigable questions shed light on how these human communities were organized?

I presently find two theoretical perspectives useful in thinking about these research questions. The first is evolutionary ecology, including human behavioral ecology, which holds that human behavior over the long term can be accounted for in evolutionary terms. The second is structural Marxist theory, which focuses on the human relations of resource acquisition, and control of production and distribution, on a shorter-term time scale. My personal experiences compel me to view pastoral stockowners as part of regional ecosystems, responding to the non-negotiable demands that weather and herd animals make on them. Likewise, my own experience compels me to see pastoralists as participants in social, economic, and ideological systems that both mediate and clash with environmental trends and that affect their day-to-day choices in managing livestock, households, and social relationships. My perspective allows "production" as both an ecological and a social concept, switching perspectives from one to the other in an attempt to view people and animals in both conceptual worlds and granting that animal remains might "make sense" in either or both theoretical contexts.

In the abstract, these theoretical worlds are rather compatible, since human behavioral ecology and Marxist paradigms share a fundamentally economic approach (see also Bird and O'Connell 2012). Both have a concern with the costs and benefits of effort exerted by humans in achieving goals within a social milieu, although viewed in very different ways and calibrated with different currencies. Sometimes these two paradigms grate against each other in troublesome ways. This friction produces interesting insights that I see no reason to eliminate, by favoring one in place the other – or even asserting that it is imperative that a single theoretical perspective "win out" over another (Conkey and Gero 1997). The present book's aims exclude exploring these aspects of theoretical consonance and dissonance further.

One more theoretical inclination should be noted: I have written this book in a way that discloses my personal standpoint, rather than invoking a neutral, objective "voice of authority" for my opinions. This is not because I believe my opinions are superior to those of others, but rather because I want to take responsibility for those times I do go out on a limb. I am mindful here of Orwell's (2013 [1946]) essay, "Politics and the English Language," with his appeal for the personal responsibility of direct prose, and Haraway's (1997) analysis of the "modest witness" mode of scientific writing that may cloak opinion in an seemingly objective style. I agree with neither writer on some points, but both have made me to be more directly accountable for passages that voice my own point of view.

1.3 This Book's Aims

This book's intellectual framework builds upon my 1991 article, which I had hoped would help clarify what I saw as some murky problems in assigning causation using zooarchaeological evidence (Gifford-Gonzalez 1991). In my own thinking, I found it useful to move systematically from the concrete individual specimen, with its surface modifications and so forth, out to the fullest kind of contextual reconstruction one might ever hope to make of past human life from such materials, including social and ecological relations. I proposed a schematic framework (Gifford-Gonzalez 1991: Fig. 2) with which to conceptualize zooarchaeological materials and the inferences we wish to draw from them. That same orientation organizes this book and will be discussed in detail in Chap. 3.

One of the most important contributions a book like this can make is to offer a means of *organizing knowledge*, both old and new, to enable understanding of the significance of new findings and to facilitate systematic research in a coordinated way. I believe that the approach articulated here allows one to fit new information, whether one obtains it oneself or gathers it from other researchers, into an intelligible intellectual structure. New discoveries that merit concentrated attention today soon are folded into our scientific practice as “givens,” and current debates may be passé in a year or two book. My hope for this book will provide students of zooarchaeology with such a framework that will be helpful to them long after most of the hot new topics in this text are old news.

This book’s second aim is to provide the reader with an *array of tools for addressing zooarchaeological research problems* using vertebrate remains. No prescribed outline exists for defining zooarchaeological research questions, identifying key variables to address them, collecting relevant data, and drawing inferences from them. I would not venture to propose one, because zooarchaeological research will never involve a simple set of instructions. Each case will demand different methodological and theoretical approaches to address the research questions and circumstances of the assemblages studied.

Instead of step-by-step “recipes,” we might imagine what a well-equipped “toolkit” of conceptual and methodological approaches should contain to address the ranges of research problems that we can expect to encounter and pursue. This is what I hope to share through detailed chapters that follow describing bone’s intrinsic properties, modifications to bone surfaces, recording zooarchaeological data, and key issues in working with such data in aggregate. This approach is manifest in Chap. 25, since inferring social relations from zooarchaeological material mobilizes many tools outlined in earlier chapters as well as some new conceptual ones. A table in the book’s final chapter will summarize tools in the toolkit, with relevant references. As with this book’s overall structure, my hope is that these will be an enduring – and evolving – contribution to readers’ toolkits for their own work.

1.4 Some Basic Definitions

It is useful to define several terms that will be used frequently in this book. *Zooarchaeology*, defined as the study of animal remains to elucidate archaeological questions (Olsen 1971), is one of several disciplines that study faunal remains.

Zoologists study living organisms, but they can use shells, skins, teeth, bones, and other constituents, including stable isotopes and DNA, to assess the age, sex, health status, and taxonomic relationships of individuals, regional populations, species, and higher taxonomic groupings. *Paleontologists* study the preserved remains of ancient animals to learn more about their evolution, systematic relationships, and ancient ecology. *Zooarchaeologists* study faunal remains from deposits created by humans at some time in the past. Here I define *zooarchaeologists* as practitioners with training *as archaeologists* who pursue their research with animal remains. I differ in in this from my friend and colleague R. Lee Lyman, who has a broader, and equally valid, definition that assigns the term to all analysts of animal remains from archaeological sites, regardless of the disciplinary training of the practitioner (Lyman 2016a, b). With Lyman's definition, zooarchaeology began decades earlier than the mid-twentieth century starting point on which I focus here (see Chap. 2).

Archaeologists working with animal remains have in fact labeled themselves with a variety of names, including archaeological faunal analysts, *osteoarchaeologists* (Uerpmann 1973) and *archaeozoologists*. These terms need a bit more clarification. In the early 1970s, when I began to study animal remains from an archaeological viewpoint, we called this kind of work "faunal analysis" or "archaeological faunal analysis." These are still accurate terms. I have chosen to use the term "zooarchaeology" throughout this book for two reasons: it lends itself more gracefully to adjective and adverb forms than do these other phrases, and it expresses well the specific type of faunal research we do: archaeology using animal remains.

Persons preferring the label "zooarchaeologist" tend to be concerned primarily with what animal remains say about humans' interactions with them. They have their primary academic background in archaeology and may have supplemental training in zoology or paleontology. They may spend considerable time describing and comparing patterns of bone breakage, cut marks, and other modifications. They normally devote less time to details of species classification, seeing themselves primarily as archaeologists who happen to use animal remains as a way of researching human adaptation and history. Most researchers cited in this text fall into this category.

Other researchers who work with archaeological faunas prefer the term "archaeozoologist." Archaeozoologists tend to be more interested in the evolutionary and ecological status of the animals found in archaeological sites and generally less concerned with what bones can tell us about details of human behavior and social relations. They focus on reading the history of certain species, such as wild cattle, from their remains in sites, on morphological and size transitions from wild to domestic forms of some species, and on regional variability of ancient domesticates. Persons preferring to be called archaeozoologists often obtained their primary training in the biological sciences rather than archaeology. They are inclined to approach archaeological assemblages as well-dated local samples of the species of interest, to be compared to other archaeological samples by detailed metrical and morphological analyses. Human modifications to bones such as butchery marks, breakage, and evidence of cooking were not heavily emphasized (von den Driesch and Deacon 1985; Bökönyi 1984), nor are detailed reconstructions of human behavior necessarily seen as a major goal. Thus, as their name implies, archaeozoologists aim more toward constructing the zoology of ancient faunas from archaeological sites.

Although it oversimplifies a complex situation, most North Americans studying archaeological faunas would probably, if pressed, call themselves zooarchaeologists, while many but not all continental Europeans would probably call themselves archaeozoologists. British researchers may select either of the two labels. Some bone researchers, preferring to reserve detailed taxonomies for their faunal collections, are content with the label "faunal analyst." The title of the journal *Archaeozoologia*, published in Grenoble, France, reflects the dominant perspectives in continental Europe.

Notable exceptions to these simplistic dichotomies exist. Some U. S. researchers have engaged in both kinds of work (Frison 1970, 1974; Grayson 1984b, 1991; Grayson and Delpech 1998; Wheeler 1982, 1984; Zeder 1991, 2001), and some continental European faunal analysts focus more on reconstructing behavior (Grayson and Delpech 1994), often in collaboration with North American researchers. Some European researchers have questioned the underlying assumptions of "animals-first" analyses (Legge 1978; O'Connor 1996). Moreover, with time, younger researchers on all continents are converging more in their interests. I expect the dichotomies that held true in the late twentieth century will not survive long in the twenty-first.

Returning to terms used in this book, it is sometimes helpful to refer to all studies of animal remains regardless of goals or the disciplinary grounding of the practitioners. In this book, I will use *faunal studies* or *faunal analysis*, to signify any research with animal remains, whether undertaken by zoologists, paleontologists, physical anthropologists, or archaeologists, regardless of aims. Mainly to have a word that can readily be used as an adjective, I will use the term *archaeofauna* to refer to a sample of faunal remains recovered from an archaeological site. This use follows Grayson (1984a) and is less cumbersome than phrases like "archaeological faunal remains." I will use this term for historic archaeological faunas as well as more ancient prehistoric samples, although "archaeofauna" may not resonate as well for some when applied to Monticello's animal remains as when used for samples from Olduvai.

The term, *archaeobiology*, includes not only zooarchaeology but also study of all ancient biological material, including that from animals, plants (in the U.S., usually called paleoethnobotany) or microorganisms not readily divided into either realm.

The term *taphonomy* has already been used in this chapter and requires further definition. It was coined by Soviet paleontologist I. A. Efremov (1940) to describe studying animal remains to elucidate their circumstances of deposition or to better define the agencies that modified them before deposition. The term is derived from the Greek words for burial (*taphos*) and rules or system (*nomos*). Considerable overlap exists in concepts and analytic methods in vertebrate taphonomy and contemporary zooarchaeology, and researchers in each area communicate and engage in projects that blur the boundaries between these fields. As noted earlier, from a paleontological taphonomist's point of view, human modifications to animal remains, as well as human actions that influence their burial, are just another set of forces affecting biotic materials. From the point of view of an archaeologist, taphonomic analyses are essential for distinguishing traces of human action from those of other creatures or natural processes that can affect animal remains. Taphonomic research will therefore be prominently featured in this book, and its history will be sketched in Chap. 2.

Finally, some basic terms should be defined. At the outset, it is important to distinguish between a skeletal *element* and a *specimen*, as these terms will be used in this book. An *element* is an anatomical unit in a vertebrate body, such as a humerus or a femur. A *specimen* is an actual archaeological remain of an element, as recovered and studied, which may be either a whole element or, more commonly in archaeofaunas, a portion of an element. I follow Lyman in arguing that terms such as "bone" or "tooth" are too imprecise, as is "fragment," for much of formal zooarchaeological writing.

When referring to humans, their ancestors and their close relatives, this book will use the term "hominin," the vernacular form the *tribe* Hominini, a level of classification between that of the subfamily (i.e. Homininae) and the genus (e.g. *Homo, Australopithecus*). This results from a taxonomic reclassification of humans and their nearest relatives in the 1990s, largely as the result of new genomics findings on of living species (Wood and Richmond 2000). It parallels many other, molecularly-based taxonomic reclassifications of vertebrate groups. While only humans, their ancestors and collateral relatives were formerly placed into the family Hominidae, under this revised systematics, all great apes are also included. The African apes are grouped with *Homo, Australopithecus, Paranthropus* and other former "hominids" within the subfamily Homininae, again based on genetic evidence for the greater similarity of these groups to one another than to the orangutan (*Pongo pygmaeus*). Below this classification is the tribe Hominini, which includes *Homo, Australopithecus*, et al., plus the genus *Pan* (chimpanzees and bonobos). These two species have the greatest genetic similarity with us and only 5–6 million years of evolutionary divergence. Practically, this means that most paleoanthropologists now refer to what were formerly called "hominids" as "hominins." Although I use the term "hominin" throughout the text, many references and some quotes in this text include the older "hominid" because it was current during the time articles or books were written.

1.5 A Caveat and a Perspective

Before turning to hundreds of pages of single-minded examination of vertebrate faunal remains, it is necessary to acknowledge the importance of other types of evidence for human subsistence, behavior, ecology, and social context. This is especially necessary for someone who wrote an article entitled "Bones are not enough" (Gifford-Gonzalez 1991). Animal remains are only one line of evidence concerning human environment, subsistence, and behavior. The last half-century of anthropological research on people who gather and hunt has shown the importance of plant foods in their diets, to say nothing of the centrality of plant foods among farmers or members of horizontally and vertically integrated complex societies. Thus, paleoethnobotany has equal importance as zooarchaeology in research on human diet and resource use. Isotopic analyses of human remains can provide a wealth of specific dietary information to complement faunal and botanical evidence from archaeological contexts (Chap. 22). Ultimately, all biological data serve limited and rather pedestrian uses if not juxtaposed with artifactual, architectural, and settlement data within a well-reasoned analytic framework. For a variety of reasons, one should play off the significant information derived from faunal assemblages against other types of archaeological and contextual data (Chap. 3).

1.6 Organization of the Text

This book is divided into five parts, each containing several chapters that fit together topically, and one concluding chapter. The purpose of Part I is to develop an orientation to zooarchaeology. This chapter begins by situating archaeological faunal analysis in relation to archaeology as a whole, by distinguishing zooarchaeology from related research fields that use animal remains, and by defining terms and concepts fundamental to zooarchaeology. Chapter 2 recounts how zooarchaeology came to be a distinct specialization within archaeology, primarily in anglophone countries, charting themes and foci of archaeological faunal analysis research in North America and the United Kingdom, but also considers the important influence of continental European researchers. It sketches development of other key regional zooarchaeological research traditions and steps toward greater communication among zooarchaeologists worldwide. Chapter 3 presents the perspective on zooarchaeological analysis that organizes this book. Concepts and themes discussed include uniformitarian methodology, actualistic research, and analogical reasoning in archaeology, a product-focused approach to bone analysis, and a forensic approach to inference of causal agency and context. My perspective is necessarily idiosyncratic. However, I arrived at many of these conceptual components simultaneously with other colleagues working in parallel. The overall perspective presented is thus one I believe is shared by many zooarchaeologists, and I will attempt to stress points of agreement and disagreement. This chapter also presents terms and distinctions useful in understanding the processes that create patterning in archaeological faunal assemblages and their relationship to the contexts in which the actors we study existed.

Part II reviews uniform features of vertebrate bodies that allow zooarchaeologists to reason productively from archaeofaunas. Skeletal elements in vertebrate bodies vary in construction, shape, density of bone tissue, patterns of growth, and associated soft tissues. These variations are properties that zoologists, zooarchaeologists, and paleontologists use to identify an animal's species, age, sex, health status, and, sometimes, even season at death. Although their properties develop as part of living organisms, skeletal elements' structure, bone mineral densities, and associated soft tissues can govern their postmortem fate. These determine an element's attractiveness of bone-modifying animals, including humans, and its response to postmortem biological and non-biological forces acting upon it. One can work with these traits in formal terms, learning to distinguish species' bones by their distinctive shapes. However, deeper functional understanding of the traits makes methodological sense: if relational analogies are stronger than formal ones, analogies based on functional relations in life or postmortem lend greater level of confidence to inferences.

Chapter 4 reviews qualities of bone and teeth that develop as functional properties of living animals, explaining fundamental variations in bone as a material. Chapter 5 describes bone's nutrient functions in living animals, specifically in mammals, and the nutrient potential of animal bones, for carnivorous organisms. Chapter 6 introduces distinctive functional patterns of osteological growth according to species, sex, and age and provides a brief overview of sources for determining species, age, and sex. Chapter 7 reviews how patterns of dental growth in mammals permit determination of age and addresses some of the complications of ageing based upon dental traits.

Part III outlines analytic approaches of zooarchaeology, from field recovery through sorting and data recording to fundamental quantitative descriptions of bone samples. These practices bring specimens under study, produce data from them, and store specimens and their data. Chapter 8 provides a brief overview of recovery and processing of bones and other faunal remains. Chapter 9 deals with how analysts divide an assemblage into identifiable versus unidentifiable components, and the consequences of such decisions for all later manipulations of data in the zooarchaeological literature. It discusses the usefulness of specimens that fall between specimens identifiable to element and species and fragments so broken that they can only be identified as vertebrate bone. Chapter 10 introduces basic zooarchaeological counting units: Number of Identifiable Specimens, Minimum Number of Elements, Minimum Number of Individuals, Minimum Animal Units, outlining the strengths and weaknesses of each.

Part IV presents specific evidence used to infer the causal processes, effectors, and actors of bone modification, to use terminology introduced in Chap. 3. In keeping with a product-focused perspective, it concentrates on the distinctive traces at the effector-actor level of inference. Some taphonomic traces on bone are so distinctive that they can be linked to specific causal processes, effectors, and actors with relatively high levels of confidence. Others, such as breakage patterns and abrasion, cannot be attributed to a single actor, and this section offers examples of how zooarchaeologists incorporated more than one independent line of evidence to narrow the range of possible causes for such ambiguous evidence. The role of various actors and processes in transporting, dispersing, or aggregating faunal remains is reviewed in Part V.

Chapter 11 outlines bone breakage and its causes, emphasizing this as a specific case of the concept of equifinality, first noted in Chap. 3. It reviews how bone structure interacts with static, dynamic, and torsional stresses, and how various actors may produce similar effects. Chapter 12 reviews the multiple effects of mammalian carnivores in terms of bone surface modification and selective destruction of sections of elements. Chapter 13 outlines the effects of other vertebrate agents of bone modification: avian carnivores such as owls, hawks, and eagles, hoofed animals, and rodents. Chapter 14 discusses distinctive hallmarks of hominin carcass dismemberment and tissue removal on bones, surveying cut marks, chops, other cutting-tool mediated marks, and percussion marks. It notes traces of non-hominin origin that closely resemble those inflicted by humans. Chapter 15 considers marks of culinary processing, as well as the nutritional gains and social aspects of this uniquely human way of handling of animal bodies. Chapter 16 briefly reviews microbial ("bioerosion") and geological effects on bone, especially abrasion and weathering, and more briefly, transport, burial, and diagenesis. Chapter 17 builds on the preceding chapters of Part IV, exploring how zooarchaeologists have worked with bone assemblages likely to have been accumulated or modified by multiple actors. Chapter 17's consideration of the challenges of analyzing archaeofaunas created by multiple actors and processes forms a bridge to Part V's focus on element frequencies and other types of aggregate data used to infer behavioral, social, and ecological contexts.

Following the scheme laid out in Chap. 3, Part V discusses methods applied to studying the behavioral, social, and ecological contexts in which archaeological faunal samples were created. Such contexts are the ultimate goal of most zooarchaeological analysis, and inferences at this level depend upon aggregate patterns of data, not simply of a single type but of multiple types in combination. When one seeks to investigate human behavior, social relations, and ecology with archaeofaunal remains moves from discerning concrete traces of effectors and actors to reaching toward the contexts in which these were produced using aggregate data (Fig. 3.1). How to develop and implement these steps is an area of active controversy. This section does not aim to resolve this, but rather to point out key arguments and steps toward consistent methods.

The first two chapters of Part V consider two key aspects of working with the complex datasets needed to address behavioral, ecological, and social contexts. Chapter 18 returns to quantification in zooarchaeology, considering the limitations of common counting and data aggregation tactics outlined in Chap. 8. It reviews commonly used methods of statistical comparison and inference using aggregate data and working with archaeofaunal counting units or other, such as nutritional utilities and bone mineral densities, variables to be introduced in this section. Chapter 19 introduces butchery in the broader context of carcass transport by humans and other carnivores, comparing tool-assisted carcass segmentation, or dismemberment, to natural processes of post-mortem disarticulation. It outlines early zooarchaeological efforts to use element frequencies as proxies for humans' transport of such body segments from their original locales.

Chapter 20 details zooarchaeological attempts to calibrate associated nutritional values of bone elements to explain human choices in selecting or discarding specific body segments. Chapter 21 reviews how archaeologists have sought to distinguish such nutritionally motivated, selective transport from in-place destruction of skeletal elements, according to their differing bone mineral densities and resultant durabilities. It revisits relevant issues concerning quantification.

Chapter 22 reviews traditional approaches to studying ecological relations from aggregate zooarchaeological data, including species abundance and diversity, and the use of mortality profiles to discern hunters' prey choice and domestic herd management. These analyses also depend upon element frequencies but use other forms of secondary data, namely relative taxonomic abundances, age-at-death data aggregated into mortality profiles, and other derived data. Chapter 23 outlines a range of new methods that enhance more traditional zooarchaeological approaches to ecology, as well as highlighting the emerging importance of zooarchaeology in historical ecology and conservation. Chapter 24 reviews widely applied approaches to archaeofaunal data based upon behavioral ecological theory. Chapter 25 aims to do two things. First, it uses zooarchaeological case studies that place animals in their human socioeconomic contexts, from foragers to farming and pastoral societies to complex, urban systems of production and distribution. Second, the chapter emphasizes the "toolkit" of conceptual and analytic tactics used to study animals in such political economic contexts.

Chapter 26 concludes with some observations on the future of zooarchaeology, as it increasingly incorporates methods from genetics and geochemistry and develops research relative to wildlife management issues. It emphasizes the need as a sustained practice for integrating zooarchaeology with other fields, offers some recommendations for approaching and executing analysis, and presents a perspective on the enduring features of the field in a time of great methodological change. This book includes some citations of publications dating up to 2016–2017, but the cut-off date for a more comprehensive literature review is effectively 2014.

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Chapter 2
The Emergence of Zooarchaeology

This chapter outlines the growth of zooarchaeology, including regions, research themes, and persons contributing to it. In what follows, recall that zooarchaeology was defined in Chap. 1 as the analysis of archaeological faunal remains by persons trained as archaeologists, contrasting with a more liberal definition that may include analysis of faunal remains from archaeological sites by persons trained in other fields (e.g. Lyman 2016a). Vertebrate remains played leading role in prompting questions about earth and human history in eighteenth century Europe and in establishing great human antiquity less than a century later (Daniel 1975; Davis 1987; Grayson 1983). By the early 1860s systematic archaeological research into association of humans with Ice Age fauna, along with wide scholarly acceptance of Darwin's and Wallace's theory of organic evolution by natural selection, produced new perspectives on the human past and the concept of "pre-historic" archaeology (Lubbock 1865; D. Wilson 1851, 1862). From this tipping point in European intellectual history onward, excavations explicitly aimed at recovering evidence of prehistoric humans began. Vertebrate remains played a major role in defining the chronology and environmental setting of Pleistocene sites.

Although animal remains were central to archaeological reconstructions of environment and subsistence from the mid-nineteenth century, their full potential for elucidating human lifeways was not realized for another hundred years. In the intervening span, archaeologists referred shells, bones, and other animal remains to zoologists and paleontologists for identification. Understandably, such specialists preferred more complete archaeofaunal specimens that would facilitate taxonomic identification. They produced lists of taxa present, with or without estimates of their relative abundances. While these are definitely useful (Lyman 2016a), archaeofaunas' potential for informing on human life were seldom taken up.

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2.1 Pioneers Who Built Modern Archaeofaunal Analysis

Zooarchaeology emerged as part of a broadening of archaeology's traditional emphasis on architecture and artifacts to encompass regional-scale site survey, geological, and biological evidence, as well as more socially focused approaches to interpretation (Trigger 2006). Increasingly affluent post-World War II economies in North America and Europe funded field investigations and founded or enhanced research institutes, academic programs, and conferences (Trigger 2006). By the late 1940s, multidisciplinary fieldwork programs were organized to focus on topics in human history that only archaeology could elucidate: the origins of farming and the emergence of social complexity and urbanism (e.g. Willey 1953; Braidwood and Howe 1960). Theoretical inspirations for these new directions lay in pre-Second World War scholarly writings (e.g. Childe 1942; Steward 1936, 1938) and prompted development of regional survey methods, paleoethnobotany, zooarchaeology, geoarchaeology, and other specializations.

In 1950s and 1960s, certain paleontologists and zoologists in several countries of the industrialized West began exploring the more human-oriented side of archaeofaunal analysis. In 1956, the U. S. National Academy of Sciences sponsored a conference on "The Identification of Non-Artifactual Archaeological Materials." Participating zoologists Barbara Lawrence, Charles Reed, and Paul Parmalee, all members of a specialist cohort who went on to mentor young archaeologists in vertebrate zooarchaeology – commented on the important potential of faunal remains from archaeological sites (Taylor 1957). Most importantly over the long run, most of these specialists began training archaeology graduate students in their own fields' taxonomic and anatomical identification procedures, as well as in ecology from a zoological perspective. With their mentors' encouragement, these students developed archaeological careers focused on archaeofaunal remains.

2.2 Regional Traditions in Archaeology

Despite coincident postwar motivations for archaeological research in Western societies, early zooarchaeological research developed within divergent academic contexts and perspectives in North America, Britain, and continental Europe. Differences in history and context often caused challenges when specialists from these regions began interacting and collaborating, and these still can contribute to misunderstandings, so reviewing them is useful. In the United States, Canada, and, often in Australia, prehistoric archaeology usually resides in departments of anthropology, with ethnology and other anthropological endeavors. In Britain, continental Europe, Asia, and Africa, sometimes in Canada and Australia, prehistoric archaeology is usually not allied with anthropology but rather in its own department or allied with history. In Latin America, archaeology may be linked with ethnology or history, or both.

For archaeologists in former European settler colonies in North America, Australia, and Latin America, the connection between ethnography and archaeology appeared to be a natural one. Aboriginal peoples were present when museums and universities' academic departments were founded. North American departments of anthropology in the early 1900s often sought to link living aboriginal peoples with archaeological evidence of their ancestors (Boas 1902), and early North American ethnographers emphasized material culture in aboriginal peoples' lives. Archaeologists trained in such contexts could imagine that social and cultural information was implicit in archaeological artifacts, as articulated by Walter W. Taylor (1948) and the "new archaeologists" (e.g. Binford 1962).

Similar bonds between ethnology and archaeology are evident in Latin American nations. However, in many Mesoamerican and Andean countries, national narratives stressing distinctively *mestizo* cultural heritage in the modern state influenced archaeological practices. State research funding has long focused the development of indigenous civilizations. While most foreign archaeologists' investigations have shared this focus, some have researched prehistoric hunter-gatherers. Latin American academics have tended to take a more historical approach, for a long time influenced by nineteenth-century European evolutionism, including, in some countries, Marxism. This resulted in theoretical divergences from Anglophone archaeologies of the capitalist North (Lorenzo 1981).

In Britain and continental Europe, the link between ethnology and prehistoric archaeology was, as stressed by Boas (1902), less "natural." European academics viewed ethnographies as relevant to peoples of colonized areas, while archaeology focused upon Europe's past (Trigger 2006). Some nineteenth-century evolutionist writers included ethnographic notes on "savages" to buttress their narrations of Europe's earliest archaeological record (e.g. Lubbock 1865; Mortillet 1897). However, twentieth-century social anthropology developed apart from archaeology, and most archaeologists saw it as having little relevance to interpreting European archaeological materials. Until late in the twentieth century, French and Continental European prehistoric archaeology was allied more with geology and paleontology than with either history or the social sciences (Audouze and Leroi-Gourhan 1981; Sackett 1981). From this perspective, faunal remains were chronological and environmental indicators, and prehistoric economic and social relations were largely inaccessible to archaeological study.

Scandinavian archaeological research consistently diverged from the general Continental pattern from early in the nineteenth century, taking a more practical approach to archaeological artifacts and sites. These were studied to learn about ancient environments and human behavior, rather than simply as relics of a stage of progressive development (Gråslund 1981; Trigger 2006). Long before English-speaking archaeologists developed such interests, Scandinavian researchers emphasized experimental replication of archaeological materials and functional understanding of ancient sites and artifacts (Trigger 2006).

2.3 Archaeofaunal Analysis in North America

Americanist zooarchaeology emerged over the 1950s through 1970s from multiple sources. As in Europe, a number of individuals trained in zoology or paleontology built major regional reference collections, wrote relevant reference literature, and trained the first cohort of young zooarchaeologists. Many participated with their archaeological protégés on the multidisciplinary investigations into major turning points in human history, which nearly always used animal remains as one central line of evidence.

Among the earliest such researchers was Raymond M. Gilmore, a mammalogist who analyzed faunas recovered by Walter W. Taylor and wrote two methodological articles on archaeofaunas (1946, 1949). The first was directed to archaeologists, while the second, on the value of archaeofaunal samples, was primarily for zoologists. Theodore E. White, trained in zoology and paleontology, while working for various government agencies published articles in *American Antiquity* (1952, 1953a, b, 1954, 1955) on differential body segment transport decisions as inferred from element frequencies in faunas derived from the River Basin Survey project, suggesting the untapped potential of faunal analysis for inferring human activities. Lyman's (2016b) biography of White suggests that, despite his relatively high and intellectually pioneering publication rate, White's lack of placement in an academic or major museum post led to a lessened appreciation of his work, given that he lacked the intellectual "progeny" common among peers in those situations.

Barbara Lawrence, Curator of Mammals at Harvard University's Peabody Museum, engaged in zooarchaeology during the 1950s, through her own analyses of archaeological materials from North America and the Near East and her encouragement of archaeology students to study bones (Rutzmoser 1999). She published one of the first guides to post-cranial artiodactyl skeletons, which proved to be of great value to archaeologists (Lawrence 1951). Encouraged by Lawrence, Stanley Olsen, a paleontologist by training, carried on this tradition in the 1960s and 1970s, producing now-classic guides to the identification of vertebrates from archaeological sites (Olsen 1960, 1964, 1968, 1972a, b). Olsen (1971) was among the first to use the term "zooarchaeology" in print. Senior zooarchaeologists trained at Harvard include Richard Meadow (1974, 1980, 1984), for many years Director of the Peabody's Zooarchaeology Laboratory, and Melinda Zeder (1991, 1998, 1999, 2001). Zeder had trained as an undergraduate at Michigan, site of another long research tradition in zooarchaeology. Olsen did archaeofaunal research after moving to the Arizona State Museum, publishing on horse domestication and the origins of domestic dogs (Olsen 1984, 1985), encouraging close zooarchaeological analyses of prehistoric Southwestern faunas, and training some of the first Chinese zooarchaeologists in the 1980s.

Paul Parmalee (1965, 1985; Parmalee et al. 1972; Purdue et al. 1991), a zoologist with a strong interest in the aboriginal inhabitants of the Midwest, built a major zooarchaeology emphasis into the Illinois State Museum in his role as Head Curator of Zoology and later Assistant Museum Director from 1953 to 1973. Parmalee encouraged more complete recovery of animal remains from archaeological sites and stressed the need for accurate taxonomic identifications and the reference collections that enabled them. He trained and inspired many Americanist archaeologists at the Illinois State Museum and later at the University of Tennessee, Knoxville (McMillan 1991). With John Guilday and others (1962), he authored an influential study of animal bones from the Eschelman Site, a historic Indian site in Pennsylvania, that demonstrated species-specific patterning in cutmarks.

Elizabeth Wing developed the Environmental Archaeology Laboratory at the Florida State Museum. Trained in biology, Wing had in her late teens worked summers with Barbara Lawrence at Harvard's Museum of Comparative Zoology. During her long tenure at the Florida State Museum she developed comparative collections for the southeastern U.S., Caribbean, Central America, and South America, emphasizing animal, plant, human skeletal, and soils analysis. She stressed archaeofaunas' dual potential to testify to human adaptations and to the historical ecology of otherwise undocumented wild species. Wing contributed many analyses of archaeological materials with a historical and anthropological emphasis, also documenting ecological histories of Caribbean species from a more zoological perspective (Wing 1978, 1989; Wing and Scudder 1980; Wing and Wheeler 1988). Wing trained many students who either went on to become practicing zooarchaeologists, such as Elizabeth Reitz (1995; Reitz and Cumbaa 1983; Reitz and Scarry 1985), or who as professionals emphasized collection of biological data in their projects, such as Kathleen Deagan (1973). Reitz and Wing (2008) and Reitz (1993) provide further details of Wing's research emphases.

Paleontologist J. Arnold Shotwell (1955, 1958, 1963) was among the first paleontologists to attempt to reconstruct community paleoecology, authoring several widely read pieces on inferring community ecology from element representation in fossil deposits, work that influenced early zooarchaeological researchers (Thomas 1971). Shotwell was an early mentor of Donald Grayson. Although Grayson (1984) has shown that some of Shotwell‘s uses of quantitative data are inappropriate, his research has expanded and refined themes found in Shotwell's, such as quantitative assessment of faunas and biogeography (Grayson 1977a, b, 1998).

Zoologist Hildegarde Howard worked with avifauna from archaeological sites, the most famous being the Emeryville Shellmound originally excavated by Nels Nelson (Howard 1929; Broughton 1996). Her illustrations of avian osteology continue to be valued by archaeologists, and she deeply influenced Grayson's interest in archaeological bird remains (D. Grayson, personal communication 2002). At the University of Washington, Grayson in turn was graduate mentor to R. Lee Lyman (1984, 1985). Grayson's many students have contributed to bone density and nutritional value research (Kreutzer 1992) as well as applying behavioral ecology to aboriginal faunas in various regions (e.g. Broughton 1994, 1997, 2002; Nagaoka 2005, 2002; Butler 2000, 2001). Later in his career, Grayson turned to evolutionary questions in comparing Neanderthal and modern human foraging in southwestern France (Grayson and Delpech 1994, 1998).

From the 1970s through 1980s, the University of California, Berkeley produced its own cohort of zooarchaeologists within a distinctive intellectual tradition. With three Cambridge educated scholars running the “Old World Prehistory” program, theoretical approaches partook more of that tradition than U.S. processualism (see Sect. 2.4), while UCB’s Americanist faculty long resisted processual approaches in their program (see Gifford-Gonzalez 2010). Africanist archaeologists J. Desmond Clark and Glynn Isaac, with paleoanthropologist F. Clark Howell, developed an interdisciplinary training program with campus geologists, paleontologists, and zoologists. Prospective faunal analysts studied with paleontologists Joseph T. Gregory, William A. Clemens, and Donald Savage. Some UCB zooarchaeology students, including Robert Blumenschine, Henry Bunn, and Curtis Marean, focused on zooarchaeology of early hominins in Africa, while others, including Diana Crader, Fiona Marshall, John Olsen, and myself, concentrated on the zooarchaeology of Holocene peoples in various parts of the world.

2.4 Beginnings of Archaeofaunal Analysis in Europe

In the 1930s, researchers at Cambridge University embarked on practices that would by the 1960s and 1970s have impacts on global archaeobiology. Prompted by pioneering Scandinavian studies in palynology, geographer Harry Godwin used pollen recovered from the peat bogs, or fens, of eastern England to reconstruct British vegetation from the last Ice Age to historic times. In 1932, Godwin and his wife Margaret founded the Fenland Research Group, an informal association of specialists, including archaeologists, interested in the evolution of the British landscape (Fagan 2001). The group emphasized human responses to dynamic postglacial landscape changes as well as later land modification during agricultural colonization. In the 1930s, archaeologists set their goal as investigating “man-land relationships” (Burkitt 1933), prefiguring environmental archaeology. Young Cambridge archaeologist Grahame Clark (1936, 1938) for the first time juxtaposed evidence of late Pleistocene to early Holocene reindeer hunters of the Northern European Plain into the detailed environmental context given by archaeobotanical evidence from that area. This integration of archaeological and environmental data in Britain was interrupted by the Second World War.

In 1952, Clark succeeded to Cambridge’s Disney Chair in Archaeology, then among the most influential professorships of archaeology in the British Isles. In writings and public presentations, Clark presented an agenda for an environmentally oriented archaeology to address forager ecology and the origins of animal and plant domestication. He argued for its centrality not only for environmental reconstruction but also to understanding human resource use, or, “palaeoeconomy” (Clark 1952). He swiftly laid the practical foundations for analysis of archaeobiological evidence. Clark hired reentry student Eric Higgs, a former farmer, to organize a faunal analysis laboratory and offer lectures (Fagan 2001). Cambridge graduate students under Higgs pioneered actualistic studies of farming and herding communities (MacEachern 1996). Cambridge graduates friendly to archaeobiology, including Geoff Bailey, Clive Gamble, Paul Halstead, Anthony Legge, and Peter

Rowley-Conwy, the latter two focusing on zooarchaeology, moved to major teaching posts in U.K. (Fagan 2001). Clark's approach might have remained strictly a regional tradition, had he not persuaded other young Cambridge archaeologists to take up fieldwork and employment opportunities in Africa, Australia, Oceania, Southeast Asia, and North America, where they also encouraged this approach. Later, Cambridge graduates and others criticized Clark's approach as offering an overly reductionist, environmental determinist perspective on forager and farmer economies (Clarke 1976; Hodder 1985).

The University of London's Institute of Archaeology, established soon after the Second World War, was another British center for training archaeologists in archaeofaunal analysis. From its inception under V. Gordon Childe, the Institute sponsored investigations into the origins of agriculture, with laboratories and staff dedicated to analysis of plant and animal remains as well as of ceramics and other artifacts. Institute staff published some of the first and most widely read books on archaeofaunal; I. W. Cornwall's (1956) *Bones for the Archaeologist* aimed to educate archaeologists in basics of animal bone sorting and to encourage more young archaeologists to develop skills in faunal identification. Widely published Institute students of zooarchaeology include Simon Davis (1987) and Terry O'Connor (2000). Universities to which students of these core institutions migrated also became major centers for zooarchaeology today.

Zoologically trained researchers in British museums published on archaeofaunas from the mid-twentieth century onward. Juliet Clutton-Brock, then head of the Mammals section in the Natural History Museum (Britain), continued an active interest in animal domestication in Eurasia and Africa, producing many publications (1993; Clutton-Brock and Griggs 1983; Clutton-Brock and Noe-Nygaard 1990). Caroline Grigson, based in the Odontological Museum of the Royal College of Surgeons, London, maintained an active career pursuing archaeozoological research on Eurasian and African faunas (1969, 1996). They co-hosted the fourth, 1982 International Council of Archaeozoology (ICAZ) conference in London.

Directly paralleling the United States trajectory, an even earlier in some cases, as continental European institutions recovered from the ravages of the Second World War, a cohort of zoological, paleontological, and veterinary science researchers pioneered archaeological faunal analysis and training students. This cohort included Joachim Boessneck (1969), Elisabeth Schmid (1972), Anneke Clason (1968, 1972), Achille Gautier (1980, 1984, 1986), Hans-Peter Uerpmann (1973, 1978; Uerpmann and Uerpmann 1997), Pierre Ducos (1968), Angela von den Driesch (1972), and Sándor Bökönyi (1970, 1983). European archaeozoologists established programs for training the next generation of analysts in various countries, including then-West Germany, Belgium, the Netherlands, and Switzerland. In the process, they developed reference collections for analyzing archaeological samples, established standards for the recovery of faunal materials, and introduced standardized methods for measuring and comparing them (von den Driesch 1976). These researchers often collaborated with one another and communicated with eastern European, British, and U.S. researchers working on parallel problems, initially on later periods of prehistory and early history in Southwest Asia and the greater Mediterranean.

Though meticulous in their work, most European archaeozoologists did not venture far into the roles animals played in the social and cultural worlds of the humans who interacted with them (Gifford-Gonzalez 1986). In an early exception, Uerpmann (1973) argued that economic and cultural information could be recovered from bone assemblages and advised colleagues to shift to what he saw as more interesting historical and anthropological questions.

In 1971–1973, this European group founded the International Council for Archaeozoology (ICAZ), which now meets in a conference every four years and, now with a truly global membership, is the central international organization for faunal analysts (see Sect. 2.6 below).

2.5 Influence of Major Research Projects on Zooarchaeology 1950–1975

Grant-funded projects investigating hominin origins, peopling of the Americas, the transition to farming, and origins of urbanism never set out to create new disciplinary specializations nor to develop analytical methodologies in those specialist fields. However, these projects ultimately did just that. Faunal analysts found they needed to consider how to interpret element representation, animal mortality profiles, bone modifications, and the effects of taphonomic processes to answer central questions posed by their projects. The recognition of common interests and goals among faunal analysts working on various projects prompted conferences, working groups, and new organizations. The need to share comparable data with peers led to emergence of more formalized zooarchaeological method and theory.

2.5.1 Agricultural Origins

Because faunal evidence was seen as integral to answering research questions concerning agricultural origins, field projects on this topic created a "market" for analysts with archaeological training and faunal identification skills. During the 1950s and 1960s, U.S. researchers fielded several multidisciplinary projects on the origins of agriculture and social complexity in Southwest Asia and the Americas. These built on multidisciplinary research pioneered by Alfred Kidder (1945) in Mayan regions during the 1930s and by Gordon Willey (1953) in the Virú Valley, Peru, in the late 1940s. Several incorporated Julian Steward's (1938, 1955) notions of cultural ecology and underlying mechanisms of subsistence change into their research designs.

Dexter Perkins and Patrica Daly, who in the 1960s divided their time between the University of Pennsylvania Museum and New York University, worked with Braidwood in Turkey and Ralph Solecki at Shanidar Cave, Iraq, encouraging archaeology students from both institutions to concentrate in zooarchaeology. These included Peter Bogucki, Pamela Crabtree, and Douglas Campana. The University of Pennsylvania maintained an active zooarchaeology presence in the Museum Applied Science Center for Archaeology into the twenty-first century.

Barbara Lawrence and zoologist Charles Reed worked as faunal analysts on Robert Braidwood's project in Iraq's Zagros Mountains foothills (Braidwood and Howe 1960; Braidwood et al. 1961). Archaeology students who participated in Braidwood's multiple projects were among the first zooarchaeological specialists in the U.S. Harvard students Richard Meadow and Melinda Zeder, trained at the Peabody Museum, also worked on research projects in South and Southwest Asia. Independent scholar Richard MacNeish's research in the Tehuacán Valley of Mexico, on which Kent Flannery (1968a, b) served as a faunal analyst (Byers 1967), began a long history of zooarchaeological analysis as an integral part of research on agrarian origins in Mesoamerica.

The University of Michigan, through its connection with these projects and those developed at the University of Chicago, supplied archaeologically trained zooarchaeologists, including Brian Hesse (1982a, b, 1990; Hesse and Wapnish 1985), Richard Redding (1978, 1981, 1991), and Jane Wheeler (1976, 1982, 1984), all of whom focused on the role of animals in emerging food-producing economies or in complex, urbanized societies. Michigan students benefited from training with Museum of Paleontology vertebrate paleontologist Carl Hibbard.

Zooarchaeology was further encouraged by the emergence of processual archaeology in the U.S., with Binford's (1962, 1964, 1965) adaptation of Leslie White's (1959) neoevolutionist perspective and Kent Flannery's (1965, 1968a) emphasis on ecosystems. Reitz and Wing (2008) offer interesting insights into the role of Walter W. Taylor (1948, 1957) in bringing botanical, zoological, and other experts into project research design.

In the mid-1960s, the British government funded The Early History of Agriculture Project, collaboration among several departments of archaeology in Great Britain, with its faunal component based at Cambridge. Higgs and his students (Higgs 1972; Higgs and Jarman 1975; Jarman et al. 1982; Legge 1972) explored techniques for diagnosing hunting selectivity and herd management from faunal assemblages in archaeological and contemporary cases. Researchers at the Institute of Archaeology, University of London, also participated in agricultural origins research during the directorship of V. Gordon Childe, 1946–1956, and even more intensively with development of zooarchaeology and paleobotanical laboratory programs.

2.5.2 Peopling of the Americas

The question of the earliest human settlement of the Americas and the Paleoindian period also prompted zooarchaeological research. In the 1960s, some Canadian archaeologists argued that broken and abraded bones in Pleistocene river gravels of the Yukon were pre-Clovis artifacts (Jopling et al. 1981). Since the bones were not associated with lithics, archaeologists on both sides of that emerging debate focused on distinguishing distinctively human bone modifications from those caused by other agents. Canadian research on this topic included experimental replication of bone modification (Bonnichsen and Will 1980; Bonnichsen 1979, 1983; Morlan 1983). While most workers ultimately concluded that the Pleistocene Yukon materials were non-artifactual, their research paralleled discussions of broken and abraded bones in early hominin bone deposits in southern Africa.

Distinctive Paleoindian projectile points and sites were recognized in the U.S. from the 1920s, and after the Second World War, they were increasingly documented in North, Central, and South America. The first such sites discovered comprised projectile points associated with the remains of extinct elephants, camels, bison or other megafauna. It was logical that the bones became a focus of attention. Joe Ben Wheat (1972) produced an influential study of the Olsen-Chubbuck site, a Paleoindian bison kill-butchery locale. His reconstruction of seasonality, hunting tactics, and butchery practices from pollen, sedimentology, bone distributions and mortality profiles stimulated behavioral reconstructions at other sites. George Frison (1971, 1974, 1978) and his students (Frison and Todd 1987; Wilson and Davis 1978) developed a tradition of detailed spatial and faunal analysis and behavioral inference, investigating mass bison kills ranging of paleoindian to protohistoric age. Frison‘s background as a cattle rancher and a hunter gave him an unequaled practical perspective on animal behavior, hunting, and carcass processing (Frison 1991). He also experimentally assessed the efficiency of Paleoindian point replicas during elephant culling in Zimbabwe (Frison 1986). Frison’s long tenure at the University of Wyoming and collaborations even after his retirement produced many students who elaborated on analysis of element frequencies, bison age determination and mortality profiles, taphonomy, and carcass “refitting” with spatial analysis (Chap. 25) as a an aid to butchery studies e.g. (Todd 1983; Reher 1974).

2.5.3 Human Origins Research

By the 1960s, Africa was recognized as the source of the earliest human ancestors. Influential physical anthropologist Sherwood Washburn and colleagues argued that present-day political problems and social dilemmas had their roots in our evolutionary history, and that these could be better understood through paleoanthropological field research and comparative primate studies (Washburn 1960; Washburn and Hamburg 1965). European and North American government and private research foundations funded human origins research in Africa and Asia, ultimately contributing to the development of zooarchaeology. Researchers seeking to discern hominin effects in Plio-Pleistocene fossil bones looked to the literature on vertebrate taphonomy, which had been developing in paleontology since the 1930s. Historical reviews of taphonomic literature can be found in Behrensmeyer and Kidwell (1984), Gifford (1981), and Lyman (1994).

From the 1940s, Raymond Dart, anatomy professor at the University of Witwatersrand, South Africa, and describer of *Australopithecus africanus*, popularized his controversial views on the evolutionary roots of human nature. Dart asserted bone- and horn-wielding, carnivorous hominins deposited the animal bones in australopithecine-bearing caves of South Africa, and also inflicted murderous damage on their own kind with these tools (Dart 1949). Dart stressed that because element frequencies in these caves did not match those of the vertebrate skeleton, being dominated by limb bones often broken into sharp fragments, this reflected australopithecine selectivity. Permutations of Dart's arguments appeared in the popular book, *African Genesis* (Ardrey 1961).

South African C. K. "Bob" Brain of the Transvaal Museum developed research on the taphonomy of South African cave deposits and did actualistic research during the 1960s. *The Hunters or the Hunted? An Introduction to South African Cave Taphonomy* (Brain 1981) synthesized his many years of experimental observations and analysis of paleontological samples. Many of his findings undermined Dart's contentions. Brain was especially helpful to younger researchers working in other parts of Africa.

Multidisciplinary human origins projects often brought together students of vertebrate paleontology, paleoanthropology, and zooarchaeology in field camps and museums. Recognizing their common interests, just as workers on agricultural origins, they began collaborating on method. Among this cohort was Harvard-trained paleontologist-sedimentologist Anna K. (Kay) Behrensmeyer, undertook taphonomic fieldwork as part of multidisciplinary projects on hominin and hominoid evolution in Kenya and later in other African and South Asian localities. She used contemporary observations and experiments to better understand the origins and nature of fossil deposits (Behrensmeyer 1978, 1983; Behrensmeyer et al. 1986; Behrensmeyer and Chapman 1993). British paleoanthropologist Andrew Hill, from the University of London, initially studied patterns of bone modification (Hill 1980, 1989), and his collaborative work with Behrensmeyer on carcass disarticulation and dispersal on modern land surfaces arose from initial discussions in the field in East Africa (Hill 1979a, 1979b; Hill and Behrensmeyer 1985).

Others from the U.S.A. working in East Africa in the late 1970s included Harvard University graduate student Richard Potts and New York University physical anthropology student Pat Shipman. While Potts and Shipman were each working with fossil animal bones from Olduvai Gorge, they recognized marks of stone tools on specimens at the same time (Potts and Shipman 1981). Bunn (1981) simultaneously recognized cut marks on fossil specimens from Lake Turkana and Olduvai. Shipman made an epochal contribution to zooarchaeology by applying scanning electron microscope (SEM) protocols to defining distinctive signatures of various bone modifiers (Shipman 1981; Shipman and Rose 1983, 1984).

Several influential contributors to the zooarchaeology of human origins developed faunal analytic skills only after working for some time as archaeologists. After a highly visible career in the 1960s as a champion of U. S. "New Archaeology," Lewis Binford started working with faunal remains in the 1970s as the result of his reflections on archaeological methodology (Binford 1983). Binford did bone-focused ethnoarchaeology (Binford 1977, 1978, 1981), arguing that animal bodies and bones were uniformitarian materials, the study of which in contemporary settings could elucidate the behavioral meaning of archaeological faunal assemblages.

Binford proposed approaches to "economic anatomy" of mammals that have been subjects of much productive debate (Chaps. 20 and 21).

Richard Klein, a University of Chicago student of F. Clark Howell and Sherwood Washburn, initially researched Russian Middle Palaeolithic archaeology (Klein 1973). From the 1970s on, Klein worked with South African Pleistocene and Holocene archaeofaunas, contributing to the paleoenvironmental record of southern Africa, and to humans' interactions with other species (Klein 1973, 1975, 1980, 1984, 1986). Klein and his students, especially Kathryn Cruz-Uribe (Klein and Cruz-Uribe 1984; Klein et al. 1983), developed approaches for ageing animals (Chap. 7), reconstructing mortality profiles, and inferring predation patterns (Chap. 22). John Speth turned to faunal analysis after an earlier career in lithic analysis at the University of Michigan. His work on seasonal needs for fat in the human diet and its probable influence on predation patterns (Speth 1983, 1991; Speth and Spielmann 1983) strongly influenced interpretations of archaeofaunal assemblages (Chap. 5).

2.6 Convergence and Communication

In 1971, a conference entitled "Domestication Research and History of Domesticated Animals," was hosted in Budapest by Hungarian archaeozoologist János Matolcsi with the assistance of Sándor Bökönyi, bringing together many European faunal analysts. In 1974, Dutch archaeozoologist Anneke Clason organized a second such meeting in Groningen, Netherlands. These led to the official founding of the International Council on Archaeozoology (ICAZ) in 1976. Initially, most ICAZ meetings focused on later periods of prehistory or historical time in Europe, but it was not long before the quadrennial ICAZ meetings included sessions on the faunal studies aimed at understanding ancient foragers and hominin adaptations (Clutton-Brock and Griggs 1983). In the early years of ICAZ, the various regional traditions of archaeological faunal analysis sometimes seemed like ships passing in the night. However, focused sessions on common areas of concern and the consistently congenial atmosphere of ICAZ meetings led to clearer communication. Now a thoroughly international organization, its governing board includes members from all regions of the world.

The 1975 Annual Meeting of the Society for American Archaeology saw its first symposium in the western hemisphere that brought together European and North American zooarchaeologists working on material from Southwestern Asia and western South Asia (Zeder and Meadow 1978). In 1976, Behrensmeyer and Hill organized a conference on taphonomy and paleoecology sponsored by the Wenner-Gren Foundation for Anthropological Research. This brought together senior researchers in paleontology, ecology, and geochemistry, including C. K. Brain, Everitt C. Olson, and P. E. Hare, with younger researchers working in Africa and Asia, including Hill, Behrensmeyer, Klein, Gifford, geochemist Lawrence Tieszen, paleontologist Elizabeth Vrba, and ecologist David Western, resulting in the book *Fossils in the Making* (Behrensmeyer and Hill 1980).

In 1984, Robson Bonnichsen and Marcella Sorg organized the International Bone Modification Conference in Carson City, Nevada, sponsored by the Center for the Study of Early Man, University of Maine at Orono. This brought together North American researchers on bone modification with Africanist archaeologists and paleontologists, resulting in another definitive volume, *Bone Modification* (Bonnichsen and Sorg 1989).

By the 1980s, zooarchaeology was a regular part of sessions at national and international archaeological societies, and zooarchaeologically based articles were frequently published in leading journals. In the late 1980s through the 1990s, a series of overviews of zooarchaeology and related fields were published, marking a new level of methodological systematization, if not uniformity, in approaches (Lyman 1994; O'Connor 2000; Reitz and Wing 2008; Chaix 2005; Hesse and Wapnish 1985).

2.7 The Emergence of Zooarchaeology in Other Regions

This chapter has concentrated on faunal studies in Europe and North America, as these regions saw the first emergence of modern zooarchaeology. However, other traditions should be acknowledged, both for their long, if often interrupted, histories of faunal analysis and for their current participation in the global research and data sharing that characterizes zooarchaeology today.

2.7.1 Spain

In Spain, a strong tradition of vertebrate paleontology existed for most of the twentieth century. From 1907 to the Spanish Civil War (1936–1939), the *Junta para Ampliación de Estudios* (JAE) funded young Spanish scholars' study travel to foreign museums in Europe and Argentina, integrating Spanish paleontology with mainstream contemporary practices (Pelayo 2007). Through various close relationships with French paleontologists and institutions, Spanish researchers became involved in describing important fossils from southern France. Programs in archaeology, often allied with history, were established in major universities and younger scholars were also funded by the JAE to study abroad (Diaz-Andreu 1995). Archaeological studies focused largely on late prehistoric and historic Mediterranean sites. Except in the case of palaeolithic sites, archaeological and animal bone-based research did not overlap.

The Spanish republic suffered a *coup d'etat* in 1936 and three years of Civil War ensued. With the inception of the Falangist regime (1939–1975), the JAE was shut down, and many Spanish academics, especially those from regions and institutions loyal to the republic, fled into exile in Europe, Latin America and the U.S.A. Those remaining in Spain were relatively poorly funded and isolated from the foreign contacts, even after the end of the Second World War. Economic conditions in Spain improved in 1960s and early 1970s, but the Franco government's generally low investment in education and policies of intellectual isolation did little to stimulate growth in archaeology, much less zooarchaeology. A few researchers, Spanish and foreign, published zooarchaeological analyses during the 1960s, setting methodological standards (Altuna 1963; von den Driesch 1972; von den Driesch and Boessneck 1975); for more details, see Morales Muñiz (2002).

Starting in the late 1970s, the post-Franco government of Spain's parliamentary monarchy invested in improvements to education and scientific research. Especially after Spain joined the European Community (predecessor of the European Union) in 1986, government stipends for doctoral or postdoctoral study abroad were restored and international scholarly travel was facilitated. Spanish departments of archaeology developed quickly in this period, and paleoanthropological specialists, often in departments of paleontology, increased. In the 1980s and 1990s, government fellowships renewed the tradition of sending Spanish faunal analysts, both paleontologists and zooarchaeologists, for postdoctoral training overseas. Fuller exploration of Middle Pleistocene deposits at Atapuerca commenced, and the spectacular discovery of many nearly million-year-old hominin remains at Atapuerca's Sima de los Huesos highlighted Spanish paleoanthropology, palaeolithic archaeology, and zooarchaeology (Fernández-Jalvo et al. 1999), as have overseas research in paleoanthropological and zooarchaeological research by Spanish teams (e.g. Domínguez-Rodrigo 1997; Domínguez-Rodrigo et al. 2001, 2007). The Laboratory of Archaeozoology in the Department of Zoology, Autonomous University of Madrid, was among the first such labs to be founded in Spain, by Arturo Morales Muñiz, who in 1972 obtained a Bachelor's degree in Biology from UCLA, later studying in Denmark, and obtaining his doctorate from Complutense University, Madrid in 1976 (e.g. Morales Muñiz 1988, 1993, 2002; Morales-Muñiz and Roselló-Izquierdo 2008). Spanish researchers have been active in ICAZ, and Morales Muñiz convened the first ICAZ Bird Working Group.

2.7.2 Israel

Israeli paleontologists and zooarchaeologists have contributed sophisticated studies on economic anatomy (Bar-Oz and Munro 2007), taphonomy (Bar-Oz et al. 2005; Horwitz and Smith 1988; Rabinovitch 1990; Stiner et al. 1995), pre-modern hominin subsistence, early sedentism (Bar-Oz and Munro 2007), and the origins of domestic animals, often working with both European and North American investigators, as will be noted in later chapters (Shahack-Gross et al. 1997; Belmaker 2005; Bar-Oz et al. 2005). A number of senior archaeologists who trained in Israel and did postdoctoral studies Europe, such as Ofer Bar Yosef, encouraged younger Israeli scholars and researchers from overseas to engage in zooarchaeological and taphonomic research. Israeli zooarchaeologists have been active participants in ICAZ meetings and often work in collaboration with foreign researchers working. For a history of zooarchaeology in Israel and Palestinian research in the West Bank up to the early 2000s, see (Horwitz 2002).

2.7.3 Mexico

In Latin America, two centers of zooarchaeological training and practice, Mexico and Argentina, are notable. Interest in archaeofaunal remains emerged with the discovery from 1882 onwards of Pleistocene mammal remains in the Valley of Mexico, and the much later discovery of human remains associated with obsidian tools and mammoth remains at Tepexpán, on the shores of the former Lake Texcoco (Corona 2008). Archaeofaunal studies developed through several impulses, originally through the efforts of Manual Gamio in the 1920s and 1930s. One of the first trained Mexican archaeologists, Gamio had been a student of Franz Boas at Columbia University, New York, introducing stratigraphic excavation and advocating a holistic view of humans in their environmental setting (Corona 2008). The next decades saw a number of exiled Spanish scientists working with archaeofaunas from Pleistocene and later sites in Mexico. In 1952, the Department of Prehistory was founded within the Instituto Nacional de Historia. Corona (2008) attributes to the efforts of a biologist turned archaeologist, José Luís Lorenzo, who had been influenced by Gordon Childe and cultural geographer Frederick Zeuner. The first laboratory for conducting zooarchaeological research in Latin America was formally established in 1963, and comparative collections built up under the direction of its founding director, a mammalogist.

Modern zooarchaeological practices were largely developed and conveyed through the efforts of Óscar Polaco Ramos, who taught at the National School of Biological Sciences at the Instituto Politécnico Nacional. Although without formal advanced degrees, Polaco introduced several generations of the students to broad-ranging zooarchaeological and zoological investigations, using contemporary methods (López-González 2008). With his students, Polaco wrote many papers on Mexican archaeofaunas from Pleistocene times onwards (Polaco and Arrojo-Cabrales 2001; Polaco et al. 1998), sponsored actualistic taphonomic research (Polaco and Heredia 1989; Polaco et al. 1988), and was instrumental in developing the analyses and displays featuring fauna from the offering deposits of the Aztec Templo Mayor in the heart of Mexico City (Guzmán and Polaco 1999; Polaco et al. 1989). Polaco's former students and colleagues in INAH have carried on strong zooarchaeological traditions (Guzmán 2008; Valadez Azúa and Pérez Roldán 2011) since his untimely death in 2009 at the age of 57 (López-González 2008).

2.7.4 Argentina

Argentina has some of the oldest archaeological sites in South America, and Argentine naturalist Florentino Ameghino was probably the first to use bone modification evidence to argue for human butchery of Pleistocene fauna (Mengoni Goñalons 2007; Ameghino 1880). Ameghino's credible claims were obscured for many years, largely as a result of the influence of the Smithsonian Institution's powerful physical anthropologist Aleš Hrdlicka, who rejected an early indigenous occupation of the Americas (Mengoni Goñalons 2007). After a long span of culture-historic archaeology, in the 1970s young archaeologists aspired to work with animal bones. As in other areas, these pioneer zooarchaeologists worked with paleontologists, especially Eduardo Tonni and Alberto Cione of the Museo de La Plata, on hunter-gatherer and indigenous agropastoralism in northwestern Chile (Mengoni Goñalons and Yacobaccio 2006). Argentine zooarchaeologists looked to Europe and North America for models and began to publish methodological articles and substantive findings. From the 1976 military coup through the restoration of civil government in 1983, Argentine departments of anthropology were decimated by arrests, disappearances, and emigration as faculty and advanced students fled for their lives. With the return of civilian government, Argentina saw a "boom" in zooarchaeology and taphonomy as academic programs were rebuilt. This swift recovery was largely due to the influence of a few younger researchers, among them Luís Borrero and Guillermo Mengoni Goñalons, who had taught themselves zooarchaeology by reading foreign journals and corresponding with overseas researchers during the period of repression and later had a hand in curricular reconstruction. In the 1980s and 1990s, Argentine researchers obtained Fulbright or Argentine government fellowships to study with zooarchaeologists in the U.S. and Europe, and foreign researchers made short teaching visits in Argentina, establishing traditions that continue to the present. Increasing numbers of Argentine researchers attended meetings of ICAZ and the Society for American Archaeology, holding posts in both organizations, and the 2014 ICAZ meeting was held in San Rafael, Argentina.

Despite weathering severe and ongoing economic dislocations, Argentina remains a center of excellence for training in zooarchaeology and taphonomy, with strong publication profiles in zooarchaeology and taphonomy. Argentine researchers have done actualistic research on economic anatomy (Mengoni Goñalons 1996; De Nigris and Mengoni Goñalons 2005), bone modification (Elkin and Mondini 1996; Mengoni Goñalons 1982). taphonomy (Borrero 1990; González et al. 2012; Borrero et al. 2007; Mondini and Muñoz 2008) and site formation (Muñoz 1997), as well as investigating long-term forager ecology (Gutiérrez and Martínez 2008), often using models drawn from behavioral ecology (Borrero 1989a, b), Pleistocene megafaunal extinctions (Borrero 2008). Argentine researchers have applied stable isotope analysis to explore forager mobility and historical ecology (Yacobaccio et al. 1997; Barberena et al. 2009). Mengoni Goñalons (2007) and (Mengoni Goñalons 2010); Gutiérrez et al. (2007) present reviews of the history of Argentine zooarchaeology and taphonomy.

2.7.5 Japan

Japan's archaeological tradition has followed its own distinctive path for many years (Ikawa-Smith 1980; Matsui 2008). Japanese researchers have used faunal remains to infer seasonality and subsistence since the 1980s, developing analytical traditions for local species (Koike and Ohtaishi 1985; Yoneda et al. 2002; Koike and Ohtaishi

1987). Hiroko Koike, now a senior researcher at the Kyushu University Museum, Fukuoka, Japan, has moved with co-researchers into using archaeofaunal evidence to assess the historical ecology of currently endangered species. In the process, they have expanded their collaborations to US, Canadian and Russian research partners (Eda et al. 2012; Nishida et al. 2012). Japanese zooarchaeologists publish in international journals have been frequent participants in ICAZ meetings for many years, and a Japanese team won the 2006 ICAZ poster prize in Mexico City.

2.7.6 China

Like some other countries noted here, Chinese archaeology in general began on a par with others and then suffered the impacts of war, social dislocation, and isolation before rejoining global archaeological practice. Modern archaeology actually began in China in the 1920s (Olsen 1987). Some Chinese archaeologists of that era obtained doctoral training abroad: Li Ji (1896–1979), who excavated the Shang Dynasty capital of Yin, near Anyang, received his PhD from Harvard in 1923. Xia Nai (1910–1985), who effectively managed the archaeological research program of the post-revolutionary Institute of Archaeology from its founding in 1950 and who assumed the institute's directorship 1982–1982, took his degree in Egyptology at the University of London (Chang 1986b; von Falkenhausen 2001). Pei Wenzhong (1904–1982), who found the first Peking Man (*Homo erectus*) cranial specimen at the Locality 1 excavations at Zhoukoudian (Pei 1934), took a two-year crash course in paleolithic archaeology at the Institute de Paléontologie Humaine, Paris, receiving his doctorate 1937 (Chang 1984).

Up to the Japanese invasion of 1937, foreign researchers excavated Neolithic, Palaeolithic, and paleontological sites using up-to-date methods, often providing on-the-job and academic training to young Chinese students who did not go abroad but instead learned contemporary principles of geology, paleontology, comparative anatomy, and archaeology in this context. The Peking Man excavations became the research focus of many foreign researchers, including Swedish paleontologist Johann Gunnar Andersson and Canadian paleoanthropologist Davidson Black. Peking University doctoral students Yang Zhongjian (1897–1979) and Jia Lanpo (1908–2001), along with Pei, worked on the project and later became major figures in Chinese paleontology and paleoanthropology, attempting to maintain international contacts during the first 30 years of the post-revolutionary period (Jia 1977; Olsen 2004).

With the establishment of the People's Republic of China (PRC) in 1948, archaeology of Neolithic and later phases was allied with history (Keightley 1977), while archaeological research on early hominins such as *Homo erectus* was seen as a scientific endeavor allied with the earth sciences. Maoist era archaeology was relatively well funded, for its value in documenting China's history as a unique and self-sufficient polity, as well as supporting a Marxist view of history (Olsen 1987). Legal oversight of excavations and research funding were strongly centralized in

Beijing during this period, and antiquities laws were strict. Major universities offered training in archaeology, but concerted archaeological research was divided between two institutions: the Institute of Archaeology, focusing on Chinese Neolithic and later complex societies, and the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), specializing in palaeolithic archaeology, paleoanthropology, and paleontology (Lin 2016; Olsen 1987). This division effectively excluded the transition from Pleistocene foraging to early food production from the official purview of either. The Institute of Archaeology was headed by Communist Party members, who theorized how archaeological evidence could be interpreted within a Marxist framework.

In terms of theory, whereas postwar Western scholars considered it necessary to explain the transitions to agriculture, urbanism, and social complexity, Marxist-Leninist perspectives on human history rendered this unnecessary, because such sociocultural developments were viewed as inevitable outcomes of universal historical processes. In terms of method, Chinese archaeologists had strong contact with Soviet colleagues over the first decades of the PRC, and researchers of later periods emulated Soviet archaeologists' extensive lateral excavations, intended to reveal more of social relations (Trigger 2006).

Yuan (2002) notes that most archaeofauna analysts in the early PRC years produced only species lists, but that a few researchers pushed faunal data further. For example, in 1956, Yang wrote "Problems of archaeological human and animal bones" in Chinese only, on methods to assess the balance between hunting and animal keeping in the Neolithic. Li and Han (1959) attempted to explore early stages of pig domestication from pig mortality profiles from the Ban-po Village Neolithic site. Beginning with Deng Xiaoping's 1978–1993 economic reforms in the PRC, Chinese archaeologists expanded contacts with other nations and disciplinary traditions. Senior academics toured Western countries and invited visits by foreign researchers in archaeology and paleoanthropology (Olsen 1987). Chinese institutions began sending young professionals and graduate students overseas for advanced training not available in PRC. Chinese antiquities laws were altered to permit foreign collaborators to work under the supervision of Chinese co-researchers, and control of antiquities began to decentralize to the provincial level.

Dr. Qi Guoqin, a member of IVPP, was sent to work with Stanley Olsen at the University of Arizona. On her return, she wrote on zooarchaeological goals and quantitative methods in an overview for Chinese archaeologists (Qi 1983) and demonstrated such approaches in her analysis of the Jiangzhai Neolithic fauna, published in Chinese (Qi 1988). Stanley Olsen continued to host Chinese scholars for study visits and to work on problems in Chinese zooarchaeology (e.g. Olsen 1984, 1985). John Olsen began a long career in East Asian archaeology during this period (Olsen 1987), continuing the University of Arizona's tradition of hosting study visits by Chinese scholars.

Expatriate archaeologist Kwang-chi Chang (Zhang Guangzhi) also maintained a long tradition of hosting Chinese graduate students and postdoctoral scholars in U.S. institutions. His many influential books on the emergence of Chinese complex societies (Chang 1980, 1981, 1986a) represented his translation and intellectual reworking of primary Chinese sources for Western scholars. In 1984, Chang returned to his native Beijing and continued his work making the archaeological approaches of one regional group intelligible to the other by lecturing on Western approaches to complex societies, including an explanation of the "New Archaeology" (Murowchick et al. 2003).

Collaborations in zooarchaeology became increasingly common. In 1988, zooarchaeologist Zhou Benxiong of the Institute of Archaeology, coauthored on archaeofaunal chickens in *Journal of Archaeological Science* (West and Zhou 1988). Yuan Jing, of the next cohort of zooarchaeologist at the Institute of Archaeology, received his doctoral training at Chiba University, Japan, in 1995. His collaborations with foreign researchers, especially in the area of animal domestication, are regularly published in English-language journals e.g. (Yuan and Flad 2002; Yuan et al. 2008). Paleoanthropologist Jia Lanpo and others from the IVPP traveled to the USA in 1986, resulting in the first Sino-American collaborative field project since World War II, on Plio-Pleistocene deposits of the Nihewan Basin, western Hebei Province. Sponsored by the Henry R. Luce Foundation, the project offered field training to young Chinese scholars now prominent in IVPP (Gao 2002). In 1992, under Luce and IVPP sponsorship and ably translated by Dong Zhuan (1997), then a doctoral student at Indiana University, U.S. palaeolithic archaeologists Kathy Schick, Nick Toth, and I presented two intensive workshops on zooarchaeology and taphonomy (Gifford-Gonzalez) and lithic technology and site formation (Schick and Toth) to Chinese professional archaeologists. Yuan (2002) viewed these workshops as important in the "formative period" of Chinese zooarchaeology.

Over the ensuing decades, Chinese zooarchaeologists have developed strong research programs not only in the Institutes of Archaeology and Vertebrate Paleontology and Paleoanthropology (e.g. Zhang et al. 2010, 2013), but also in provincial museums and antiquities services, as some have increased their funding and oversight of archaeological heritage, and many have collaborated with overseas researchers (Hu et al. 2009; Lam et al. 2010; Liu et al. 2006; Cai et al. 2009; Ma 2005; Pike-Tay and Ma 2011).

To conclude, regional traditions continue to structure research questions in zooarchaeology, in part because of the unique human histories attested by regional archaeological evidence, and in part because of the distinctive histories of archaeologists in those regions. Running through this diversity, however, is a growing convergence in analytic methodology, facilitated by international journals, conferences and workshops, and, increasingly, other kinds of online forums for communication.

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Chapter 3
A Perspective on Zooarchaeology

For the last two centuries, bones, teeth, and shells have been accepted as evidence for chronology, ancient environment, and human activities. Faunal remains are credible evidence of past circumstances because they possess properties that have not changed over long spans of time. Zooarchaeological writings often have discussed such properties of animal bodies as *uniformitarian* ones (Binford 1981:234; Bonnichsen and Will 1980; Gifford-Gonzalez 1991; Lyman 1994). While the term "*uniformitarian*" has been called into question by some zooarchaeologists (e.g. Wolverton and Lyman 2000), as will be discussed in this chapter, whatever term one prefers, studying the present to understand the past is central to zooarchaeology, and this depends upon assuming that some *temporally invariant properties of animal bodies* exist. Zooarchaeological research today many times involves experiments or other contemporary observations of modification of faunal remains, intended to serve as analogues for archaeofaunal evidence. However, working with analogues has been a controversial area in archaeology, and an orientation to zooarchaeology should include a review of such matters.

3.1 Uniformitarian Approaches

The term *uniformitarian* entered geological discourse in the 1830s, when it was used in a review of Charles Lyell's *Principles of Geology* (Whewell 1832) to describe the approach taken in the multiple volumes of Lyell's work. Lyell, who was an adherent of the so-called gradualist view of earth history and trained as a lawyer, built upon the work of earlier generations of geologists, including James Hutton (e.g. Hutton and Playfair 1785) to "make a case" against the competing "catastrophist school of earth historians (Porter 1976). Catastrophists contended that repeated and unique calamitous events on a scale unknown in our present-day world produced the observed discontinuities of faunas in successive geological deposits. According to this scenario, each such catastrophe ended a major epoch of life on

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earth, produced the differences between ancient and modern faunas (Hooykaas 1970; Simpson 1963). In *Principles of Geology* (1830), Lyell argued that all geological and, by extension, paleontological, deposits could be explained by invoking the operation of processes observable in the contemporary world, rather than by citing catastrophic events exceptional to it. Lyell's approach rested on the assumption that geological processes had remained constant in their action and effects over the entire span of the earth's history. Paleontologist George Gaylord Simpson (1902–1984) called this position *methodological uniformitarianism* (Simpson 1970).

Prior to publication of Darwin's and Wallace's theory of organic evolution, Lyell also postulated that life forms did not alter significantly over earth history, a position Simpson labeled this *substantive uniformitarianism*, noting that this did not withstand the impacts of Darwin and Wallace's model for the organic evolution of species by natural selection (Darwin 1859; Wallace 1859). In the 1860s, convinced that the latter could account for the appearance of new species, Lyell abandoned his second position regarding the static nature of organisms. Lyell's methodological uniformitarian approach remains a cornerstone of the historical sciences, including geology and paleontology.

3.1.1 "Uniformitarian" vs. "Immanent"

For those who have read Wolverton and Lyman (2000) on the use of analogy in archaeology, it may be useful to point out some similarities and differences in how they and I approach terminology, which in part stem from the respective bodies of literature upon which we have drawn. At the outset, I stress that we are in agreement on the problems with analogies that can arise when properties that are outcomes of unique historic trajectories are confused with those produced by causal processes that operate uniformly over time and space. Wolverton and Lyman rely strongly on other work by paleontologist and philosopher of science George Gaylord Simpson, notably "Historical Science" (Simpson 1963), also citing a number of works by philosopher of archaeology Alison Wylie (1985, 1989), as well as key works in the argument over analogy in archaeology that occurred in the 1980s. In my own writings on the same topic (Gifford 1981; Gifford-Gonzalez 1991), I have drawn not only on Simpson's and Wylie's writings but also on the philosophical literature on analogy, some which will be cited in this chapter, as well as the work of evolutionary biologist Ernst Mayr (e.g. 1982). In writing my 1981 review article, I also cited works on the role of contemporary observations in paleoecology, as this field had emerged since the 1960s, which also will be cited in this chapter.

One key terminological difference is Wolverton and Lyman's rejection of the term "uniformitarian," preferring instead Simpson's (1963:24–25) term, "immanent," for,

> The unchanging properties of matter and energy [chemistry, mechanics, physics] and the likewise unchanging processes and principles arising therefrom are immanent in the mate-

> rial universe. They are nonhistorical, even though they occur and act in the course of history.

In Simpson's description, these contrast with contingent or "configurational" outcomes of such immanent processes within specific and unique historical trajectories. Wolverton and Lyman (2000:234) state, "configurations are the unique expression of particular combinations of immanent processes in operation in more or less unique sequences at particular intensities on particular phenomena." Paraphrasing Simpson, they note that erosion is an immanent process but the form of any specific geomorphological feature shaped by erosion is a unique configuration of processes and outcomes.

I incline against using "immanent," to describe such properties for two reasons. First, this term has a long history in philosophy and theology, meaning not only "inherent" but also, in philosophy, a solely mental action, and, in theology, literally "in-dwelling," as it has been used since the seventeenth century. Though "uniformitarian" carries nearly two centuries of baggage, at least that baggage can be unpacked solely within the historical sciences – as with Simpson's (1970) distinction between Lyell's substantive uniformitarianism, which has been discarded, and methodological uniformitarianism, which Simpson stipulated enables our study of planetary processes.

Second, and perhaps more importantly, Simpson's 1963 discussion, referred *only* to physicochemical processes as having immanence, or operating in a law-like fashion. His article, and the conference volume in which it appeared (Albritton 1963), came at a time of ferment within the non-archaeological historical sciences, in which paleontologists were debating the limits of uniformitarian assumptions and the possibilities of formulating law-like principles for their field, anticipating by some 20 years similar debates in archaeology. Much of Simpson's 1963 essay is devoted to an insightful consideration of the concept of "scientific law" in the nonhistorical sciences and how this has structured the course of expectations in geology and paleontology. Simpson (1963:29) discusses the complications that arise for the historical sciences when they seek to emulate the nonhistorical physical sciences in discovering laws. He argues that this is "mistaken in principle," because,

> Historical events, whether in the history of the earth, the history of life, or recorded human history, are determined by the immanent characteristics of the universe acting on and within particular configurations, and never by either the immanent or the configurational alone.

Wolverton and Lyman (2000:234) state "…the processes that result in biological evolution—genetic transmission, mutation, drift, differential reproduction, survival, and selection—involve immanent properties and processes," and (2000:236) "Immanent analogies involve using laws that apply in all times and places to understand a configuration of unknown creation." DNA and RNA themselves are composed of molecules and hence governed by chemical processes that may be universal in Simpson's sense. However, from my point of view, Wolverton and Lyman's second statement would exclude all the processes cited in the former, since, if we strictly adhere to the Simpsonian dichotomy, the life processes on our planet may not be the only template for life in the universe.

One could dismiss this observation as an interesting but irrelevant quibble, but it's quite relevant to the dichotomy Wolverton and Lyman seek to develop, and to the serious issues with which those of us using analogy must grapple. DNA might not the only possible chemically based form of information transmission in living matter in the universe, but even if it may not be universally "true" off-planet, can those of us who work here on earth assume it worked the same during a specific span of earth history? That is, could we proceed on the working assumption that DNA operated more of less similarly over the span of, say, hominin evolutionary time? For this span of earth history, can we assume it has been as uniform in operation as are radioactive isotopes? Likewise, vertebrates evolved and they did not exist "at all times." Does this mean that they lack any inherent properties might hold true, when and where they did and do exist? If this were not the case, why would we do bone modification experiments to understand more of traces on ancient specimens? How can paleontologists believe themselves to be justified in diagnosing tooth marks on the 90 million year old shell of an ammonite invertebrate, and even in suggesting the dinosaur species that created them (Gale et al. 2017)?

The thinking of another philosopher of biological science, Ernst Mayr (1904–2005), provides a slightly different perspective from Simpson's on uniformity of process and, by extension, on reasoning by analogy. I owe a great debt to Kent Flannery for directing my attention to Mayr's writings in his final chapter of *Guilá Naquitz*, (Flannery 1986), in which he referred to Mayr's approach to scientific explanation. Flannery noted that Mayr's approach made more sense to him for studying the shift toward cultivation than did the reductionist approaches modeled on the physicochemical sciences, which had hitherto been held up as ideals of scientific explanation in archaeology. Like Simpson, Mayr acknowledged that biological and ecological systems must be viewed differently than physicochemical systems (e.g. Mayr 1982). Like Simpson as well, Mayr asserted that biologists do themselves a disservice if they conclude that their inability to reduce ecosystem function to simple, determinative statements reflects theoretical inadequacy. He called for acknowledgement that that different concepts and forms of explanation are necessary for biological and ecological systems. Mayr asserted that biological systems can be studied systematically, as did Simpson, but he differed in that he believed predictive statements about the outcomes of processes operating in them can be made, but that these are often *probabilistic* in their operation. Such processes would not be immanent in the way Simpson defined that term in 1963.

In discussing a methodology for studying biological systems, Mayr (1982:63–67) stressed the concept of *emergence*, which in his usage he tied to the notion that organisms and ecosystems commonly have a hierarchical organization. Emergent properties of a complex system, whether it is an organism or an ecosystem, cannot be accounted for by invoking explanations based on properties of any lower-level component. Moreover, such complex systems may exhibit behavior and organize themselves in ways that are not predictable based upon the sum of their parts. The philosophy and study of emergence in physical and biological systems is a field unto itself, and the reader may find entry point to that literature in Corning (2002).

The rather simple example of water has been used to convey the idea of multiple levels of integration and "behavior" involved in emergence. Water is composed of molecules, each typically comprising two hydrogen ions and a single oxygen ion, though variations (isotopes) exist. The behavior of water at this level is best studied by theory that treats it as a chemical compound, taking into account its constituent ions, variations in the structure and behavior of hydrogen and oxygen isotopes in the molecule. However, when water molecules exist together in gaseous, liquid, or solid states, such basic chemical concepts may not adequately account for their behavior. One must instead use physical theories of phase change to understand how, when, and why water molecules become a solid, a liquid, and a gas. When small units of liquid water such as raindrops combine into more massive bodies, predicting how they will behave another area of physical theory. Water moving downhill may move in harmonic waves and so forth. To account for its behavior of water in such aggregates and contexts, one turns to fluid dynamics, rather than relying only on bodies of theory that worked well at lower levels of integration. We know from everyday life that even sophisticated, satellite-based observations of water phase states can only give us estimated types, times of arrival and chances of precipitation.

Biologists and ecologists face the challenge of identifying and applying the appropriate theory and method to study each level of emergence and integration: that of cell components and their chemical operations, of organ systems, of organisms, and of organisms interacting together in plant and animal communities. Nonetheless, ecosystems have do have regular relationships between constituent processes and outcomes, for example, that between the amount of precipitation and standing biomass (Ogutu and Dublin 2002). Many of the components in these regularities are variable over space and time. Therefore, they are not well suited to the simple, cause-effect descriptions that work so well at molecular level.

For those of us in historical sciences such as paleontology and archaeology, the question is whether and how this approach, rather than the immanent-configurational distinction, is the best way to consider how analogical inference works in our inquiries, which, as Simpson stated, are not amenable to the "all times, all places" generalizations of the physical sciences. If this is the case, then "explanation" depends upon the level of integration at which one is working, and reasoning by analogy becomes more complicated at levels where processes operate probabilistically. The next sections of this chapter explore why this is so, and why actually making some forward progress, despite the lack of "all times, all places" generalizations on which to base all our inferences, might be possible.

To sum up this rather long detour, I agree with Wolverton and Lyman that archaeologists, who are a kind of historical scientists, must handle reasoning by analogy very carefully. I also agree with them that different kinds of analogies exist that vary in their strength of relationship to causal processes, and therefore have different limits on the plausibility of inferences drawn using them. I will continue to use "uniformitarian," or "inherent" rather than "immanent," for the reasons outlined above, which I hope will become even clearer through the balance of this chapter. I also will use the term *actualism* as do paleoecologists, who, like archaeologists, find it informative to make contemporary observations to elucidate the patterning in evidence from the past. How we parse out what can be known through such observations and what cannot is the subject of the balance of this chapter. Finally, I will introduce some distinctions used by philosophers of analogy that I have found useful in sorting out stronger from weaker analogies to zooarchaeology (Gifford-Gonzalez 1991), as has Wylie in her writings on analogy in archaeology in general (1982, 1985). In this process, I also draw upon some of Lyman's salient earlier writings (e.g. Lyman 1987).

3.1.2 Actualism

A methodologically uniformitarian approach offers the historical sciences a practical research strategy for learning more about the past, using modern analogues. Lyell argued that, if earth processes have remained constant, one could understand the origins and nature of deposits by studying processes that are forming analogous deposits in the present day. In historical sciences, and more recently in archaeology, studying present-day analogues to learn more about preserved evidence from the past has been called *actualism* (Binford 1981; Gifford 1981; Herm 1972; Hooykaas 1970; Lawrence 1971). The word may puzzle English speakers, since in English, "actually" means, "in fact." However, in contemporary German and Romance languages, the cognate means, "of the present," or "contemporary." Actualism, brought into English from its prior use German paleontology, thus refers to *studying contemporary processes and their products to assign meaning to evidence from the past*.

3.2 Reasoning by Analogy

It is useful to explore the relation of uniformitarian assumptions, actualism, and reasoning by analogy specifically in relation to the study of archaeofaunas. Animal remains are reliable indicators of past processes and contexts *only* if one takes a uniformitarian perspective. When we infer a mammal's age-at-death from an unfused epiphysis of an archaeological specimen, we assume that the same growth processes that produce such features in the present did so in the past. We interpret a carnivore tooth mark on a fossil bone by assuming that it was produced in the unobservable past in the same way as ones we can observe created today.

Through the 1960s and 1970s, archaeology saw many debates over reasoning by analogy. Some early processual archaeologists claimed that archaeology could and should move beyond analogical reasoning to inference by deduction, based on law-like generalizations (Binford 1967; Freeman 1968). Richard Gould (1978; Gould and Watson 1982) reasserted that we could "escape" from using analogies by relying on "laws," statements of invariable causal relationships in nature, derived from ecology, biology, and geology. Alison Wylie (1982, 1985), an archaeologist and philosopher of science, responded that application of law-like generalizations in explanations relies on the assumption that the processes and relationships stipulated in the law were the same in the remote past as observed in the present. This is, she argues, a special and complex form of analogical reasoning relying upon complex, uniformitarian relationships. Today, most archaeologists accept that both our methods of inference, and even how we know what we know, usually rest on analogies (Binford 1981, 1987; Hodder 1982).

One can sum up a perspective on the use of analogy in archaeology in three statements: analogy is inevitable; analogy can be abused; analogy can be refined by actualistic research. The next sections examine each statement more closely, with an emphasis on avoiding the pitfalls.

3.2.1 Analogy Is Inevitable

Working with archaeofaunal samples, we use analogy pervasively, from naming the osteological element and identifying the species from which it came to inferring details of ancient environment or ecological interactions. For example, when encountering a fossilized bone identical to a right femur of a modern deer, most researchers will automatically call the fossil a deer femur. The fossil specimen is named based upon its resemblance to modern femora, via a complex, virtually instantaneous, assessment of its relevant physical characteristics. In fact, the specimen may differ from modern deer femora in some traits, such as in its weight, color, and chemical composition, but researchers probably will decide these are not relevant to identifying the bone and the species, based upon another set of assumptions that these traits reflect postmortem taphonomic processes, while their primary concern is with its earlier, life context. So, in naming the bone they make an analogy with modern deer femora, based on relevant *criteria of similarity*.

Most paleontologists or archaeologists will take inferences by analogy considerably further. Although they did not find any other deer bones, they accept that the fossil femur once existed in a skeleton. They also infer that the ancient femur was linked to specifiable muscles, tendons, and ligaments, the quadruceps femoris and not the biceps brachii, for example, with specific locomotor functions. They even will accept that the ancient deer was a browser, with the ruminant digestive system characteristic of the species. They might go even further, inferring that the ancient deer was an adult when it died, because the epiphyses at either end of the bone were fully fused. If pushed, they would probably also accept that the bone and the entire deer's body grew from a fertilized ovum, with cells diversifying into specialized bone tissues. Given an adequate modern comparative set of male and female deer femora, they might even infer that the fossil bone probably came from a male.

By this time they will have inferred a great deal about the anatomy, physiology, embryology, feeding, and reproductive potential of an animal we have never seen, all based on one specimen. This is what philosophers call *ampliative inference*. The researchers have in fact mobilized a very complex web of analogies to infer the prehistoric existence of physical traits and behaviors that they have not actually seen. Yet, no one would believe there is much fantastic or weak about these inferences. These broad inferences are all based on this object's similarity to other objects documented in the contemporary world, and from the fact that, in the known world, objects resembling a deer femur do not come into existence and function in ways other than this.

3.2.2 Analogy Can Be Abused

However, it is possible to make less secure inferences about the ancient deer. For example, one might say that this male deer had been very reproductively successful, or that he had indigestion when he died. Intuitively, most of us would feel less secure about these inferences, because we cannot see clear linkages between the femur and these inferences – one can conceive of too many possible exceptions. This gut-level feeling tells us something about what makes a strong analogy.

Secure analogical inferences, such as those about the functional anatomy and embryological development of the deer femur, are based on clear functional links between key features of the bone and wider linkages of its contemporary counterparts. These in turn are based upon inherent properties of organisms, traits and functions that result from interaction of genetic coding with environmental context. Moreover, in the background to these linkages is the knowledge that there are no documented cases in which femora came into the world in the absence of those specified biological contexts and histories. Thus, embryological development and functional anatomy of femora are "necessary and sufficient" causes of their existence. They are the "source side" for the phenomenon we examine (Wylie 1989).

This more warranted, functionally based type of analogy has been called *relational analogy*. These rest upon stipulated functional relationships, such as structure or causation, among the phenomena described (Wylie 1985; Hesse 1966; Copi 1982). They are considered to be stronger forms of analogy than those based solely on resemblances of form, or *formal analogies*. The latter are akin to what Simpson (Simpson 1963) called "configurational" properties, outcomes of historical processes that bear some resemblance to one another but lack specifiable structural or causal relationships. Drawing upon Simpson's discussion, Wolverton and Lyman (2000) called these "configurational analogies."

For some early processualists (e.g. Ascher 1961; Binford 1967; Freeman 1968), a key motivation for seeking an alternative to analogical reasoning was their dislike of questionable practices involved in archaeologists' use of "ethnographic analogy". Egregious cases attributed processual traits to a past society based upon that society's formal resemblances to an ethnographically documented group among whom those traits exist. For example, Ancestral Pueblo people living in the Four Corners region of the American Southwest are clearly related to modern Pueblo Indians, sharing architectural and ceramic traits. Some archaeologists uncritically attributed ethnographically documented Pueblo social and ideological perspectives and practices to ancestral Puebloans, without considering the effects of four

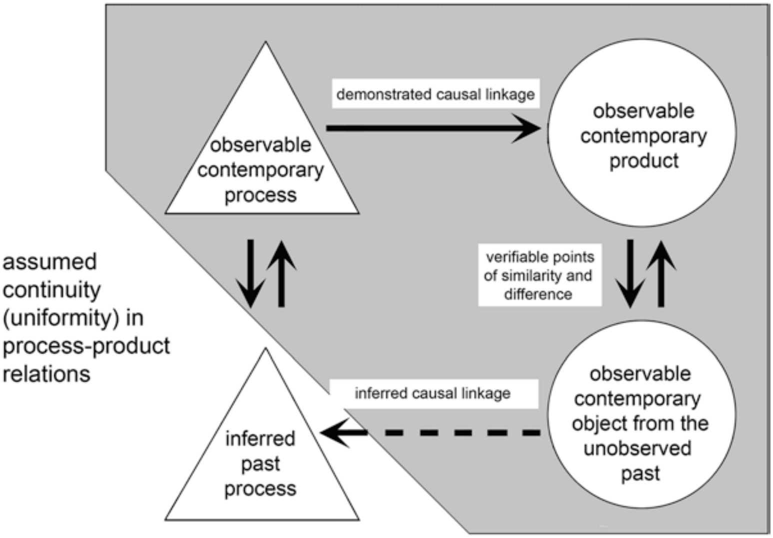

Fig. 3.1 A model of analogical reasoning in historical science. Shaded area indicates the zone of contemporary observations. The "inferred similarity" on the left may also be viewed as one or more uniformitarian assumptions. (Redrawn by author from Gifford-Gonzalez (1991:222, Fig. 3.2), used with permission of Elsevier)

centuries of colonization and resistance. Cordell and Plog (1979) challenged unwarranted assumptions of ethnographic similarity between ancient and recent Pueblo dwellers. Reconstructions of early hominin adaptations displayed parallel, problematic uses of ethnographic analogy. Isaac (1971) initially interpreted small clusters of stone tools and animal bones in Plio-Pleistocene deposits as "home base" camps like those of modern foragers. From this, Isaac inferred that similar socioeconomic relations, including food sharing and division of labor by gender, existed one-and-a-half million years ago. Binford (1981), Hill (1984), and others criticized such inferences as unwarranted, given the lack of functional links between the spatial patterning and such behavioral characteristics.

3.2.3 *Actualistic Research Can Refine Analogy*

One can explore functional and causal relationships necessary for relational analogies only in present-day situations. Only in the present can researchers observe an archaeological object and explore possible functional links between a process that we suspect may have produced such an object and its actual material products, a cause and its effects (Binford 1983: 98–100). By establishing causal linkages, one can return to archaeological materials with a sense that the analogies used to interpret them are secure. The basic relationships in using modern analogues are outlined in Fig. 3.1. Based upon certain assumptions intrinsic to our discipline, we

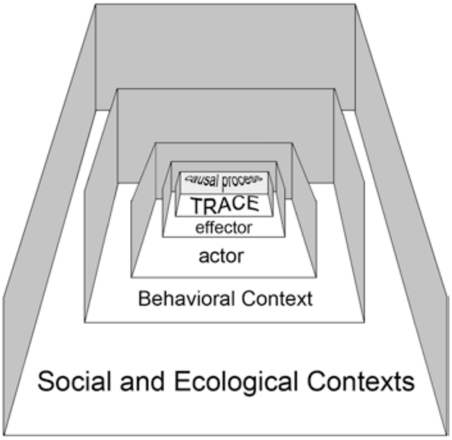

Fig. 3.2 A model of different levels of inference in zooarchaeology. (Redrawn by author from Gifford-Gonzalez (1991:229, Fig. 2), used with permission of Elsevier)

accept an object as a remnant of a past time. If some trait of this archaeological object is not completely understandable, based on our knowledge of the contemporary world, we select a modern analogue. Through comparison, we verify that the two objects are similar in aspects that we believe are relevant to our inquiry (criteria of similarity), at the same time noting traits that differ between the two (Copi 1982; Wylie 1985). Based again on our knowledge of the present-day world, under controlled circumstances, we establish which among a range of processes that might create the trait we are seeking to elucidate. We may discover that other processes than we originally imagined actually created the feature. With our new understanding of the contemporary cause of the feature, and based on the resemblance of the experimental evidence to the archaeological evidence, we infer that a similar process produced the archaeological feature in the past.

Inferring the cause of the prehistoric feature requires that we assume that similar processes have produced similar traces over long stretches of time. The practice of investigating potentially uniformitarian processes and their products by observation of modern-day analogues is actualism. At the most basic level of assigning meaning to zooarchaeological materials, we believe our inferences to be warranted, given observed relationships between dynamic causes and their static effects.

3.3 Actualistic Research in Zooarchaeology

Zooarchaeologists and paleontologists have done actualistic research on animal remains with increasing frequency over the last 30 years, reflecting their widespread recognition of the productive research relationship of analogical reasoning, uniformitarian assumptions, and actualism. This research includes *experimental archaeology* and, when humans are among the actors modifying faunal remains and creating evidence (the modifications), the study will probably be called *ethnoarchaeology*. Studies of modifications to animal remains by other actors in natural settings might be termed *landscape taphonomy*. I would include prudent use of historically and ethnographically documented *causal* relationships as relevant to establishing relational analogies, for the same reasons as discussed by Wolverton and Lyman (2000), serving as the main basis for setting up a relational analogy. However, all this rests upon having excluded all other possible causes for the effect or effects seen, and therein lies Wolverton and Lyman's objection to using essentially contingent, or configurational patterning based upon a few cases as if they were truly uniformitarian. This is especially problematic in levels of systemic integration where causal processes may operate probabilistically. Actualistic research in zooarchaeology has produced great gains in understanding bone surface modifications. Part IV of this book shows that actualistic research on bone collectors and bone modifiers has specified causal processes for many formerly ambiguous modifications, such as cut marks, tooth marks, weathering, and spiral fractures. Part V will explore how actualistic research has elucidated causes of bone element preservation or destruction of various found in prehistoric bone assemblages. However, this section also demonstrates that behavioral inferences from element frequency patterning may be problematic precisely because only human selectivity, rather than intrinsic properties of elements themselves, was assumed to be the causal process behind the patterns.

At its best, landscape taphonomy assesses the systematic processes underlying the fate of animal remains in their postmortem contexts, when not only biological agents but also weather and geological processes affect the condition and, ultimately, survival of organic remains. Bones, shells, and other remains play a role in ecosystems, as food, shelter, and otherwise useful items to various organisms. Greater knowledge of structural and functional relations of animal remains as elements in ecosystems is beginning to elucidate the pre-depositional fate of bones. One example of this is discussed in detail in Chap. 21, when a variety of processes have been seen to exert differentially destructive effects on various skeletal elements. Elements with high surface area to volume ratios are more vulnerable to weathering, trampling fragmentation, and some forms of microbial attack.

3.4 Levels of Analogical Inference in Zooarchaeology

Actualistic research may help us infer that a groove on a bone surface was made by a carnivore tooth, and even, from its size, geographic, and temporal context, that it was probably a hyena's tooth, but what does the presence of the tooth mark testify to the behavioral, social, or ecological *context* in which the mark was made? Did the hyena scavenge the bone it gnawed from another carnivore's kill or did it hunt its prey cooperatively with other hyenas, as some are known to do? These questions all pertain to behavior and ecology, and simply identifying the tooth mark does not answer them, even though one can assume that the animal lived in such contexts.

3.4.1 Causal Process, Effector, Actor, Behavioral, Social, and Ecological Contexts

This section presents several distinctions based upon Mayr's (1982) approach to hierarchically organized systems that will prove useful in later chapters on bone modifications. These also serve to introduce a product-focused approach to zooarchaeological analysis. Figure 3.2 presents a visual model for a nested set of causal relationships. Innermost is the actual *trace* that is present to study as empirical evidence. This is the product of a *causal process*. In the example discussed above, the causal process was a hyena's tooth pressing down on and moving across the surface of a skeletal element, causing the surface to give way a bit and producing a groove. One can call the hyena tooth the *effector*, the actual physical cause of the modification. Beyond this is the *actor* that creates the trace though the causal process, in this case, the hyena that did the gnawing.

Encompassing the causal process, product in the form of a trace, and the actor is the *context* in which the actor produced the evidence. The most immediate is the *behavioral context* in which the trace was produced; in the case of the hyena tooth mark, this could be "scavenging" or "predation," Beyond this are the *social and ecological contexts*, referring to the web of social (pack-living, living in a pair, solitary) and ecosystem relations in which the actor lived and acted.

Establishing a strong relational analogy that implicates a causal process, an effector, and an actor is relatively straightforward. This requires excluding other possible causes. For example, based again upon the aggregate findings of actualistic research, many vertebrate taphonomists don't think one can make infer the species of a bone gnawer from tooth marks (Fernández-Jalvo and Andrews 2016) and recommend using a more conservative and defensible inference of actor such as "large carnivore," rather than stipulating this was made by a hyena.

The real challenge comes if one hopes to use hyena tooth marks to infer whether the animal was hunting or scavenging when it gnawed the bone it had acquired. In terms of the "necessary and sufficient" idiom, neither such activity is a necessary cause of the mark. At the scales of organization described in behavioral, social, and ecological contexts, relational analogies – so valuable for the power they bring to analogical inference – are rare. Given that ecosystems and even living organisms are complex, emergent levels of biological organization, Mayr (1982) argued that one cannot account for their functioning by pursuing reductive explanations such as are common in physical and chemical sciences, and which worked so well in the example given for trace/process/effector levels. Outcomes of processes are more likely to vary and are best described by probabilistic, likelihood statements, rather than those of the "if a, then b" variety. Analogical reasoning is not impossible in these contexts, but it is much more complex, and it probably has different standards for evaluating its soundness. This presents inferential problems to zooarchaeological researchers who, as much as they are delighted to recognize tooth scores or cut marks, really want to learn more about the behavioral, social, and ecological circumstances of human ancestors. There is nothing inherent in the immediate causal relations that allow us to infer behavioral context. To paraphrase the old joke about a rural New Englander giving directions, we "can't get there from here," at least not in the way that we did with the trace-effector-actor example. The question is how *do* we get there from here, if at all?

It would be an error to conclude that one should – or could – avoid using analogies taken from modern ecology or even ethnography because of such variability and complex determinacy. It is hard to imagine how one could say much about prehistoric materials without using analogies, whether naming objects, describing their function, or defining their contexts. Wylie (1989) lays out a discerning discussion of this use of "suppressed analogy."

3.5 Using Analogy at Higher Levels of Systemic Integration

Given the complexities outlined above, prudent use of analogy involves at least three methodological tactics. The first is simply to evaluate whether specific analogies are relational or formal, thus clarifying the strength of the inferences possible. This evaluation could involve investigating systematic, functional links between classes of archaeological evidence and their causes and associated actors *in the present*. Granted, this boils down to what Wolverton and Lyman (2000) remind us are empirical generalizations, and we should never assume they have the same strength as relational – Wylie's (1989) "source side" – analogies.

In determining the causal actor or actors responsible for specific patterns in our data, it is nearly impossible to use any one line of evidence that has shown itself to be ambiguous in relation to which actor that produced it. A second tactic is to not rely on any one type of data to make a causal inference, but rather to use multiple, independent lines of evidence. Such an approach was termed *"forensic"* by Lyman (1987), emphasizing parallels to investigations in which multiple lines of evidence, each independent of the other, are brought to bear on determining the agent behind an event. The more lines of evidence point to the same causal process, effector, and actor, the more likely it is that these were responsible for the outcomes being investigated. This approach to dealing with ambiguous causal agency or circumstances has sometimes been called "contextual analysis," or described as applying independent uniformitarian "frames of reference" Binford (1987; 2001).

Often no single line of evidence unambiguously identifies an actor or context of production, but, if the preponderance of independent lines of evidence points to a given actor or context, we feel more strongly warranted in specifying it as the most likely possibility. The courtroom standard of "beyond a reasonable doubt" may thus not be a realistic standard for zooarchaeologists, but something close to such a criterion, based on the concatenation of "circumstantial evidence," may be achieved.

The key requirement for independent lines of evidence is that they may not be produced by the same process. For example, two morphologically distinct marks of carnivore teeth on a bone, pits and scores, are not independent evidence for the action of carnivores because both are produced virtually simultaneously by gnawing

(Chap. 12). By contrast, the presence of many gnawed bones and no human artifacts in a small cave more strongly suggests the activities of a carnivore. Two independent lines of evidence, the gnaw marks and the physical context, both point to the same agency or context production. Chapter 17 presents some cases of such reasoning.

The third tactic entails a longer game: doing more systematic work on constructing plausible, analogy-based arguments about the complex, higher-level systems that Fig. 3.2 calls "context." Zooarchaeologists are already doing this when they make arguments based on multiple and independent lines of evidence, such as frequencies of cut marks, osteological element frequencies, relative species composition of samples, and so forth, as will be outlined in Part V.

3.6 "Signatures" and Equifinality

Through actualistic research, zooarchaeologists have defined distinctive traces, to use the terminology of Fig. 3.2, or what are sometimes called "signatures," made by a specific actor. However, actualistic research has also shown that different causes can sometimes produce very similar final effects, requiring further research to distinguish.

The case of so-called pseudo-cut marks, or trampling marks (Chap. 13) is one such example. In the early 1980s, Shipman and her coworkers (1981; Shipman and Rose 1983) used SEM to describe multiple morphological criteria of stone tool cut marks, demonstrating that these differed from the marks of carnivore teeth. A few years later, paleontologists described similar marks on fossils from epochs predating the existence of hominins (Behrensmeyer et al. 1986; Fiorillo 1989). They also experimentally demonstrated that these "pseudo-cut marks" could be created on bones trampled by hoofed animals against a substrate with angular particles. In this case, the *causal process* and *the effector* that produced pseudo-cut marks and stone tool cut marks is the same: a sharp, angular edge of a stone dragging over a relatively fresh bone surface. However, the *actors* differed. Therefore, the inferences from the traces about effectors and actors were ambiguous.

Lyman (1987) described such cases as problems of *equifinality* ("same end" or same final outcome). Alan Rogers (2000) has pointed out that biologist and cyberneticist von Bertalanffy's (1968, 1949) original definition of equifinality refers to outcomes that are identical and can never be distinguished. Rogers makes the case that some outcomes called "equifinal" in the zooarchaeological literature are not really equifinal in Bertalanffy's sense. We will return to Rogers' important methodological point several times in this book, especially in Part V. For the present, it is sufficient to explore how zooarchaeologists deal with the very real problem of sorting out actors when effectors and causal processes are virtually identical.

The case of cut marks and pseudo-cut marks sheds light on ways of coping with the dilemma of equifinality. Rogers (2000), suggests that one should first ask whether this is a problem in the primary data (some quality of the materials that one can physically examine) or in secondary data (an issue with the derived statistical characterizations of the materials). The pseudo-cut mark example shows that it is possible to have similar primary evidence produced by different actors. In the case of pseudo-cut marks, researchers brought together several new, independent lines of evidence to better identify the most likely actor. To address this, investigators undertook a new round of research to distinguish these two traces *on the basis of other criteria than the traces themselves*. This included the substrate type: does the matrix in which the bones were found contain angular materials that could have caused pseudo-cuts when the bones were trampled? Researchers also assessed placement of the marks on the bone: are the marks in anatomically "logical" zones for butchery, or more or less randomly located on convex surfaces, where they would be in contact with angular stones if trampled? Multiple lines of evidence, each involving relational analogies based in immanent properties of the materials, work together to reduce ambiguities in any single line of evidence.

3.7 A Product-Focused Approach

This book takes a *product-focused approach* to analysis of archaeofaunal specimens (Gifford-Gonzalez 1991) that concentrates on specimens as the end-products of complex chains of events during life and after death. This includes both the various stages of the biostratinomic realm and the subsequent, *diagenetic* realm of physico-chemical transformation (see Part IV). It is a truism that paleontological and archaeological faunal assemblages have complex histories, during which many processes may act upon them. Some such processes leave traces of their operation, some do not, and some may obscure or remove the marks of others. For example, the surface of a bone lying out in open air cracks and exfoliates, removing shallow cut marks made on its original outer layer.

This sequential process of postmortem modification has been called the "taphonomic overprint" (Lawrence 1968). Earlier taphonomic writings often emphasized the progressive losses of information about life context through various postmortem processes acting on organic remains (Lawrence 1968; Meadow 1980; Clark and Kietzke 1967). This point of view is correct, as it describes the progressive, postmortem divergence of animal remains from their original contexts as constituents in living organisms. However, the "overprint" perspective suggests a chimerical goal for taphonomic and zooarchaeological analysis: that of "unbiasing" an archaeofaunal sample back to its original context in a living system.

Lyman (1994) and I (Gifford 1981; Gifford-Gonzalez 1991) have argued that this is not a realistic aim. Rather than viewing taphonomic analysis as "stripping away the overprint" from biological remains, it is more productive to focus on taphonomic effects as evidence *added* to specimens by postmortem processes. In fact, taphonomic evidence is a form of *trace fossil*, testifying to the action of other organisms and non-biological processes on organic remains. Referring to the effects of diagenetic processes on stable isotopes in bone, geochemist Andrew Sillen

(1989:228) put it this way, “Diagenesis suffers from a bad name; we tend to see it as the mist on the window rather than part of the view.” In fact, these altered materials are all we have to deal with in our analyses, so we need to follow tactics suited for learning what their preserved evidence can tell us.

A starts from the viewpoint that each specimen has an individual , some of which can be discerned from its form, composition, and modifications. These include attributes are functionally related to the specimen’s ontogenetic development and the role it played during life, while others were produced by the processes that acted upon it after death. Analysis therefore always begins with recording data from individual specimens. However, just as there is no typical archaeological site, there is no typical bone. To understand the dominant processes that created a bone assemblage, data from individual specimens must be read as an *aggregate pattern*.

Patterning in data from a faunal assemblage is thus the cumulative reflection of redundant incidents of human behavior or the action of other processes that produced certain repeated effects on faunal remains. The dominant patterns of modification should reflect at least some of the most common processes affecting animal remains as the assemblage formed. Methodologically, zooarchaeologists’ task is to understand those processes that created patterning in the data. Like other historical scientists, zooarchaeologists must also consider the possibility that some processes affecting archaeofaunal samples left few or no distinctive traces.

3.8 Types of Evidence in Zooarchaeology

Zooarchaeologists may handle bones one by one, but they almost immediately begin to derive data from them to look for the aggregate patterns of data noted above. Two basic categories of information are used in zooarchaeological analysis, upon which nearly all other abstractions of data and inferences are built.

3.8.1 Primary Versus Secondary Data

Reitz and Wing (2008) and Clason before them (1972) defined *primary data* versus *secondary data*. Primary data can be physically inspected on actual specimens and include species, age, and sex identification, presence or absence of elements and portions of elements, and modifications. Secondary data are types of information abstracted from a faunal assemblage in aggregate, such as relative frequencies of species, age structure, patterns of butchery, and so forth.

Reitz and Wing (2008) argue that primary data are more amenable to replication by another researcher and subject to “less interpretive latitude” than are secondary data. At least in the abstract, this should not be the case if secondary data manipulations are clearly enough described so as to be replicated by other researchers.

The distinction between primary and secondary data may be useful to maintain as we look at debates about the meaning of patterning in aggregate data, and debates over equifinality in archaeofaunal data, as will be discussed in Part V.

3.8.2 Element Frequencies and Surface Modifications

Nearly all the data discussed in this book can be classed as one of two other types: *bone surface modifications* and *element frequencies*. Bone surface modifications (Fisher 1995) include cuts, chops, burning, other effects of humans, claw and tooth marks and other effects of biological agents, or weathering and other geological or mechanical forces. Researchers cited in this book refer to these as the "traces" or "signatures" of various agents. Recognizing these, as well as pathologically derived markings, depends on knowledge of the modal appearance of unmodified bones. Our ability to recognize and derive useful information from such modifications has expanded tremendously since the 1970s, and much of this book will be devoted to summarizing what is known about the causes of various bone modifications, as well as unresolved problems in making plausible inferences from them.

Element frequencies are counts of specimens of skeletal elements relative to one another in a faunal sample. Statements such as, "Caribou were the most common species in the assemblage," or "Aardvarks are rare in Late Stone Age sites," are based on element frequency data. In addition to species abundances, reconstructed age-at-death profiles of animals in a sample and inferences about hunting, herd management, or seasonality drawn from them depend upon counts and reckoning the relative frequencies of age-diagnostic bones and teeth. Studies of size variation of species over time, often linked to climatic fluctuations or intensities of cropping in species of indeterminate growth (e.g. Klein 1986; Broughton 1997), depend upon totals of identified elements with metrical attributes. Studying butchery and selective body segment transport by humans, be they hunter-gatherers or market-economy butchers, also depends on frequencies of elements from different body segments. These are likewise the data on which assessing the amount of in-place destruction of more delicate bones is based. Thus, taxonomic abundance, age and sex structure, and body part representation are all different permutations of basic element frequency data.

To sum up, zooarchaeologists have only begun to address the relation of aggregate patterns of evidence to analogues in the present, and, as will be seen in Part V, the level of controversy over conclusions about behavioral, social, and ecological contexts reflects this less constrained area of inference. Fundamentally, zooarchaeologists are seeking to use such data as *proxies* for unobservable behavior or its contexts. However, other sciences such as plant and animal ecology work with aggregate data and address similarly complex relationships, many of which are not directly observable. They therefore might provide zooarchaeologists with models for doing this kind of work, as will be discussed in Part V.

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Part II
The Evidence - Vertebrate Bodies

Chapter 4

Bone and Vertebrate Bodies as Uniformitarian Materials

Bones and teeth develop as elements in living bodies and serve multiple purposes in sustaining the life of an animal. They simultaneously provide shelter for soft tissues and serve as reservoirs of calcium and other minerals, as storage depots for lipids and other nutrients necessary for survival and reproduction, as factory sites for blood cells, as structural anchors for muscles used in locomotion, and as essential tools in food acquisition and processing. Combinations of these properties govern the response of bones and teeth to stresses before and after death and their attractiveness to carnivores and other consumers. Many such traits are uniformitarian in nature, and therefore they are useful in testifying to past human activities and their contexts.

Bone possesses both rigid strength and a degree of resilience. Teeth are rigid and extremely hard but lack flexibility. These skeletal properties result from selection for individual vertebrates with skeletal structure strong enough to withstand the stresses and shocks of locomotion and eating. Hoofed animals evading predators may exert hundreds of pounds of stress on a joint or sector of bone as they run, turn, or leap at high speeds. Predators that seize large prey in their teeth must have muscles and bones strong enough to keep their heads from being dislocated from their necks as their victims struggle to escape. In horned and antlered species like antelopes or deer, males compete for access to breeding females by physical clashes of their specialized headgear. Their bones must be strong enough to withstand the impacts and torsional stresses of such encounters. Arboreal female primates such as langurs must be able to absorb the g-forces of long leaps and landings in the trees while pregnant or carrying their clinging offspring.

Bone deposition is extraordinarily responsive to physical stresses placed upon bone elements by weight-bearing and muscular contractions. It can accommodate the idiosyncratic demands of an individual's lifestyle and activities. Athletes engaging in impact sports lay down significantly more bone than do less active persons (Jones and Howat 2002) so long as they are engaged in intensive levels of the sport. In sports involving handedness, such as tennis, the playing arm can add 28–35% more cortical (compact) bone than the other arm (Jones et al. 1977). When such

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athletes' activity levels decrease, bone begins to be resorbed by the body's physiological system. Bone deposition's responsiveness to the presence or absence of stress motivates medical recommendations for continued weight-bearing exercise among older persons at risk for bone loss (Chan and Duque 2002). Numerous studies have demonstrated that weight-lifting, walking, and other activities can reverse bone loss (Barlet et al. 1995; Forwood et al. 1996).

The species-specific stresses of everyday, plus the added demands of reproduction and survival on vertebrate bodies, have over evolutionary time produced distinctive musculo-skeletal proportions, echoed in the form of individual bones and in the microscopic structure of those elements. Zooarchaeologists, zoologists, and paleontologists use these functionally based morphological traits to identify skeletal elements, their sex, age, and species from osteological remains.

The same functional properties of bones and body segments dictate how humans and other carnivorous animals must handle them. For example, the elbow and ankle joints of deer and other ruminants undergo extraordinary stress during running and leaping. They have evolved into a form that permits a limited but forceful action in a single plane. Bones, muscles, and connective tissues buttress and stabilize the joints. Ruminant ankles seldom dislocate in life due to the close fit between their distal tibia and the top of the astragalus (ankle bone), plus the joint's dense casing of tendon. This same anatomy makes the ankle very difficult for humans to dismember, and as a consequence, butchers often hack through the bones above or below the joint rather than attempt to open it at its points of articulation. Carnivores trying to carry a ruminant's meaty hind leg to a safe place for feeding often come away with the ankle as well, although these elements yield little nourishment.

Functional qualities of various bones make them more or less attractive to humans seeking raw materials for tools. For example, ruminants' metacarpals and metatarsals ("cannonbones") are reduced into a single unit of two fused bones and exhibit a dense, longitudinal arrangement of the bone osteons on the microscopic level. Their length, osteonal straightness, and strength are adaptive features in these fleet prey animals, but these traits also make them excellent raw material for bone tools such as awls and needles.

Bone elements' roles in a living animal body determine how they endure postmortem impacts. Elements with the densest concentrations of bone tissue are the most likely to withstand postmortem effects of a wide range of potentially destructive processes, including carnivore gnawing, processing by hominins, trampling, weathering, and sedimentary processes of deposition. Bones' patterns of osteon structure determine their resistance to stress in different planes. Such internal construction can be revealed by the deliberate application of acids to the bone surface to etch away the outer cortical bone and expose the underlying organization (Ruangwit 1967; Tappen and Peske 1970). Natural weathering of bone also reveals the same structures, characterized in anatomy as "split lines," as the outer layer of cortical bone exfoliates (Behrensmeyer's Weathering Stage 3 or 4, see Chap. 16).

Despite their diversity in form, structure, and function, skeletal elements share some intrinsic properties. This chapter reviews the physiological functions of bone, composition of bone, teeth, and other hard tissues of the skeleton, variations in isotopic composition of bone, bone genesis and growth, organization of bone at the microscopic level, variations in bone structure and mineral density in the vertebrate skeleton, and types of joints. These topics provide a baseline of knowledge for understanding how humans approach butchery and cooking, the effects of carnivores and herbivores on bone, the impacts of weathering and other geological processes, as well as such areas of zooarchaeological inference as age, sex, and seasonality.

4.1 Physiological Functions of Bone

In life, bone functions as a reservoir of minerals essential for proper physiological function and reproduction. Calcium and phosphorus are essential to maintaining electrolytic balance in the blood, and these are readily mobilized from bone. Female amniote vertebrates (reptiles, birds, and mammals) have bone-based systems for storing and mobilizing calcium and phosphorus during the animal's reproductive years. Female reptiles and birds need calcium and phosphates to build eggshell. They must also incorporate enough minerals and protein in each egg's amniotic sac for the offspring's prenatal body growth. This requirement imposes major demands on stored calcium and phosphates over a very short time for females that lay clutches of eggs. Birds build up extra calcium deposits in the inner (medullary) spaces of their long bones before breeding (MacGregor 1985). Among mammals, lactation places yet another, temporally extended demand for calcium and other nutrients on reproducing females (see Chap. 5). Placental mammal females have adapted to the added demand of long gestation periods, over which much fetal bone formation and growth takes place.

Biomedical studies of human female bone physiology have taken precedence over those of other mammals, but these generally reflect patterns in other placental mammals. In well-nourished and even under-nourished women, pregnancy does not deplete calcium from bone, despite demands of building a baby's bones. Rather, forms of estrogen specific to pregnancy facilitate extra bone deposition, resulting in a net gain in bone tissue (Galloway 1997). This can be seen as an adaptation to later demands of lactation, building up reserves that nursing begins to deplete in humans after 6 months. Females' elevated bone deposition during pregnancy does not depend on higher calcium intake above adult requirements. Absorption of calcium in the gut varies according to several physiological factors, among them levels of Vitamin D and estrogen. Hormonally mediated increases in calcium uptake during pregnancy appear to simply capture more calcium from the amount that would normally be excreted without absorption (Galloway 1997). Female sex hormones thus encourage bone deposition and balance the resorption of bone.

Most female mammals display progressive depletion of calcium from their bones, due to incremental bone mineral losses during successive lactations, each of which is not fully offset by the next pregnancy's cycle of deposition. Unlike most other vertebrates, human females have a long post-reproductive lifespan, during which lactation-based bone mineral loss is exacerbated by the post-menopausal decrease in estrogen production (Liu et al. 2002). Post-menopausal women in some geographic populations, particularly those with low levels of melanin in their skins, experience relatively higher rates of osteoporosis, as bone-destroying cells outpace bone-building ones (Galloway 1997).

Bone thus combines structural solidity and resilience with a dynamic physiological role, supporting an organism's bodily movements, physiological function and reproductive success. Understanding how these multiple roles are accomplished requires a closer look at the microscopic composition of bone, how bone grows from distinct precursors, how it remodels, and how bone tissue is organized at increasingly macroscopic levels up to that of skeletal elements visible in the vertebrate skeleton. Distinctive features of cartilage and teeth are also discussed. Finally, sex-, age-, and season-specific patterns of bone growth will briefly be mentioned, a topic taken up in greater detail in Chap. 6.

4.2 Basic Constituents of Bone Tissue

Bone is a compound material, consisting of a rock-like mineral component and a pliable, protein-based one. It is thus sometimes referred to as a "two phase" material (Lyman 1994:72). Bone displays mechanical properties of both constituents in its responses to stress. The mineral component, *hydroxyapatite* (sometimes called bioapatite), allows bone and teeth to resist compressive forces such as blows or impacts involved in locomotion, predation, and so forth. The protein component, *collagen*, affords bone a degree of flexibility and resilience in the face of torsional (twisting, deforming) forces to which a skeleton is subjected. Hydroxyapatite mineral is laid down in crystals and plates in and around collagen fibers, which thus serve to orient the organization of bone tissue. The ratio of inorganic apatite to collagen is about 70:30 in bone and 97:03 in teeth. Because of their high mineral content, bones and teeth have great potential for preservation in many depositional contexts.

4.2.1 Hydroxyapatite

The apatite component in bone is somewhat variable in chemical composition, with carbonate hydroxyapatite the most common: $Ca_{10}(CO_3,PO_4)_4(OH,Cl,F)_2$. Fossil bone apatites are predominantly carbonate fluorapatite: $Ca_{10}\ (CO_3,PO_4)_6(F)_2$. Fluoride, with greater electronegative properties than other constituent elements, preferentially binds to formerly living apatites from the sedimentary matrix. Hydroxyapatite crystals have very high surface areas in relation to volume, further enhancing the potential for ion exchange in bone tissues in living animals and, as a postmortem consequence, thus facilitating the chemical transformation of the carbonate mineral into the more durable, fluorine-dominated mineral (Carlson 1990).

However, hydroxyapatite readily dissolves in acids. Bone remodeling is accomplished by dissolution of bone tissue by hydrochloric acid secreted by a specialized cell, the *osteoclast* (Baron 1993:8–9). Some of us may recall the classic chicken-bone-in-soda-pop experiment in our childhood science class, in which the mineral part of a bone dissolved in the alarmingly acid pop, leaving a pliable collagen element. Acid sediments can also cause loss of bone mineral (Chaplin 1971), either completely destroying bone elements or reducing them to “rubber chicken” bones, as is often the case of bodies preserved in peat bogs.

4.2.2 Collagen

Collagen fibers in bone are precursors of hydroxyapatite deposition, the framework on and in which the mineral crystals deposit. Between 85% and 90% of all protein within bone is Type I collagen; the balance consists of non-collagenous proteins trapped in the bone structure from the extracellular bone fluid that is secreted by the osteocytes themselves (Termine 1993:22). Type I collagen is a very large molecular structure, composed of a triple helix of soft protein chains, with a molecular weight of over 300,000 (Termine 1993:21–22). In life, Type I collagen fibers are much larger and longer than the hydroxyapatite crystals aligned along and within them, especially in long bones (Fig. 4.1). The role of collagen fibers in living bone is to resist torsional stress through the “flex” provided by bending of its fibers and simultaneous transmission of force away from its point of entry through the bone via its elongated fibers.

Type I collagen is not readily soluble, contributing to its postmortem persistence in bone for extraordinarily long spans. Collagen has been recovered from bones of

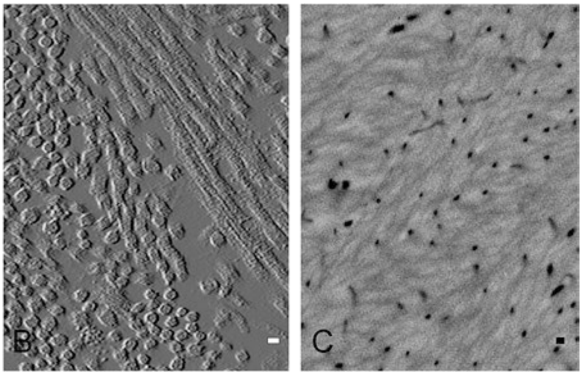

Fig. 4.1 Electron micrographs of collagen. B shows bone collagen fibrils in both longitudinal and cross-sections (scale of bar: 50 microns). C shows typical patterns of collagen in layers in bone, reflecting the ultrastructure of lamellar bone (scale of bar: 50 microns) (Images by Marian Young, in Corsi et al. (2002: 1187, Fig. 7), used with permission of M. F. Young and John Wiley & Sons, Inc.)

Quaternary (Pleistocene-Holocene) age, and even in some bones of greater age, although it eventually depletes (Zococo and Schwartz 1994). However, under specific chemical and temperature conditions, collagen fibers begin to shorten after death, decreasing bone resilience. Some studies suggest that drying, weathering, and heating all accelerate collagen fiber shortening and thus increase bone fragility (Taylor et al. 1995; Stiner et al. 1995; Richter 1986). This process will be examined in more detail in Chap. 15.

4.2.3 Stable Isotope Variations in Bone

At the more basic chemical level, bone comprises isotopes of various elements that indirectly reflect the food and environment of living animals. Since the 1970s, *stable isotope analysis* has emerged as a new field; it initially focused on human diet but more recently includes animals and their life contexts. This text will explore recent applications of animal bone isotope analysis in Chap. 23. It is sufficient here to note that various stable isotopes of carbon, nitrogen, and oxygen are incorporated into organic compounds that make up animal skeletons. Proportions of these isotopes have been shown by actualistic research to serve as proxies for the nature of dietary intake, for the latitude where foraging occurred, and for the climatic context in which bone or tooth formed. Four decades of bone chemistry research have offered new insights into the life contexts of animals. Isotopic assay now can constitute one of those independent lines of evidence necessary to narrow a range of inferences about past context.

4.3 Origins and Histology of Bone Tissue

Bone is created, maintained, and destroyed by three types of cells. *Osteoblasts* arise from a stem cell in the primordial mesenchyme of developing embryos, and they form bone. Osteoblasts contain receptors for both Vitamin D and estrogen, both of which encourage bone deposition; Golgi bodies and other organelles involved in protein synthesis are common in these and other bone cells. During bone development, osteoblasts typically cluster in tissue on the internal wall of a bone, or *endosteum*, where they secrete a bone matrix precursor that, over a period of weeks, mineralizes (Baron 1993). As the matrix ossifies, the osteoblasts become trapped in small spaces, or *lacunae*, within the bone they have deposited. They transform into *osteocytes*, or bone-maintaining cells. Their long processes to neighboring osteoblasts – also transforming into osteocytes – now run tiny channels in the bone, called *canaliculae* (Fig. 4.2). Between each osteocyte's cell membrane and the bony walls it has deposited, *bone extracellular fluid* circulates, facilitating the transport of nutrients to and from the cell and bony tissue.

Bone is permeated by open space, some visible to the eye, as in the marrow, or *endosteal*, space in long bones or in the open strut-work of *trabeculae* in spongy

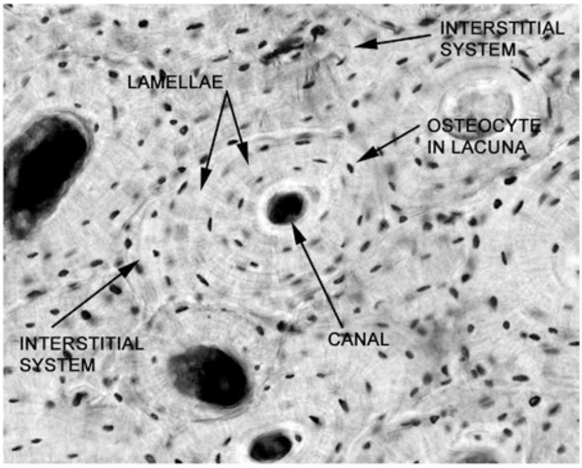

Fig. 4.2 Osteon showing central canal and concentric arrangement of bone cells, lacunae with osteoblasts and canaliculae extending out from lacunae (Micrograph by Thomas Caceci (2008), Dr. C's On Line Histology http://www.doctorc.net. Used with permission of Thomas Caceci)

bone (see below). Other, tinier spaces are visible only under magnification, comprising lacunae where mature bone cells reside and their canaliculae, as well as the spaces between overlapping plates of woven bone (see below) and that between osteons and cement. In adult humans, the total surface area formed by these spaces in bone is estimated to be 1000–5000 m^2. By contrast, adult lung capillaries have about 140 m^2 of surface area (Baron 1993:4). Thus, bone has exceptional potential for rapid turnover of bone mineral from and to the circulatory system.

Mature bone thus contains layers of osteocytes in lacunae with canaliculae extending from them. A common organization of cells in bones is the *Haversian system*, also called an *osteon* in which osteocytes are arrayed in a concentric pattern around a central canal carrying a blood vessel and nerves (Fig. 4.3). Canaliculae communicate both among osteocytes and with the central vascular chamber of the overall structure. One tubular system is joined to others by *cement*, a bone-like, noncellular material. However, as Chaplin (1971) points out, not all bone is organized in Haversian, or osteonal, systems. Flat bones and others may lack the central canals but still have lacunae and canaliculae.

Bone remodeling is accomplished with a third bone cell mentioned earlier, the *osteoclast*. This is a giant cell with multiple nuclei, thought to most likely be descended from phagocyte cells (Baron 1993). Osteoclasts create a highly acidic environment in a "secondary lisosome," or chamber lying against a bone wall, breaking down the apatite crystal with a contained zone of hydrochloric acid of higher pH than the bone tissue or the rest of the osteoclast itself (Baron 1993:6–7). Enzymatic action breaks the bonds between the hydroxyapatite crystals and their collagen bundles and dissolves the mineral and the collagen. Osteoclasts typically work within erosional lacunae (Howship's lacunae) or on inner bone walls. Bone remodeling involved in the growth of long bones proceeds in a coordinated cycle of activation, resorption, and formation (Blair et al. 2002.). After osteoclasts are activated along a span of bone, bone tissue is deleted from the inner surfaces of an element as osteoblasts begin creating new bone layers on the outer sides of the same elements and zones (Baron 1993:9).

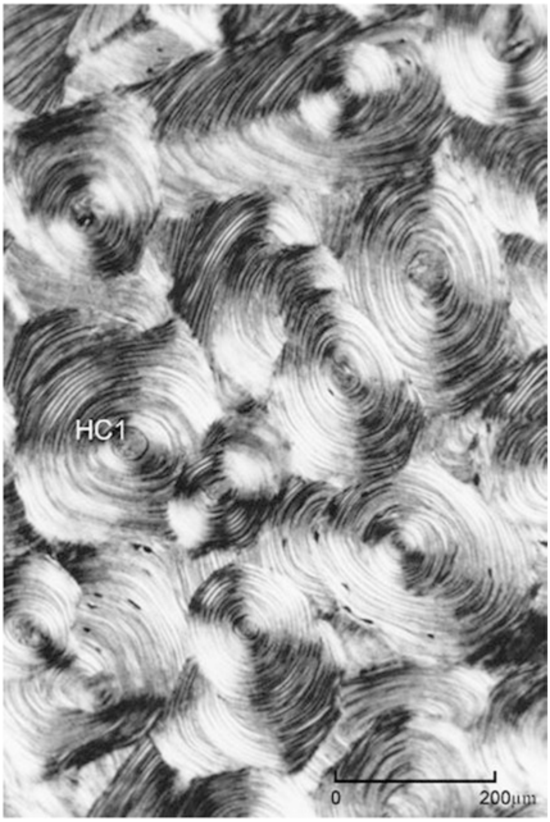

Fig. 4.3 Multiple mature osteons organized in the classic tubular form typical of compact bone. HC1: longitudinal Haversian canal. Note the accommodation of osteons' shapes to adjacent structures (From Cuijpers 2006:272, Fig. 2, used with permission of author and John Wiley & Sons, Inc.)

For zooarchaeologists, this level of detail may seem less relevant to their concerns than bone growth and its age-indexing parameters, or grosser levels of bone construction and its effects on bone durability, breakage patterns, and so forth. However, cooking, a typically human approach to extracting nourishment from bones, acts at the chemical level, extracting or altering bone tissue components. We should therefore recognize the source of nutritional gains and taphonomic impacts of cooking, as did Chaplin (1971) over three decades ago. These topics will be taken up in greater detail in Chap. 15.

4.4 Micro-Architecture of Bone Tissue

At the microscopic level, two basic types of bone cell organization exist. *Woven bone* is named for its characteristic pattern of randomly oriented osteocytes and collagen fibers. Woven bone grows quickly and is typical of fetal and neonate bones, of bone calluses repairing a fracture, and of abnormal bone surface growth and tumors.

Fig. 4.4 Mandible of immature deer (*Odocoileus*), showing woven bone growth after fracture of the dentary (Photo by author of specimen collected by Dr. Gary Haynes.)

In injuries it is produced by damage to the periosteal tissue on the outer bone surface (Fig. 4.4). Over time, woven bone is usually replaced by the second bone type, *lamellar bone*, with specific, layered orientations. Lamellar bone comprises most compact or cancellous bone structures visible to the naked eye. In both types of bone structure, the bone is organized into sets of preferentially oriented collagen fibers containing osteocytes, and these fiber groups are built up in layers (Latin: *lamella, lamellae*), in which each layer has a different preferential orientation.

A third structure in mature bone, *fibrolamellar* or *plexiform* bone, exists in some larger nonhuman mammals (Fig. 4.5). Fibrolamellar bone consists of sandwiched layers of lamellar and woven bone. It is thought to be an adaptation to large size and relatively swift growth schedules of large mammals (Lipson and Katz 1984; Martiniakova et al. 2006), but not all large mammals likely to be found in archaeological sites have it. Artiodactyls, including deer, bison, cattle, antelopes, and their relatives have fibrolamellar bone, whereas equids and their relatives do not (Cuijpers 2006). Zooarchaeologists should know about this type of bone because it differs in outer structure from commonly illustrated thin sections of osteons shown in human anatomy books, which portray only the woven and lamellar bone typical of our species.

In my own research in the 1990s on thin sections of antelope and zebra taphonomic samples from Africa, before publication of articles by Cuijpers and Lauwerier (2008; 2006), I was initially confused by bovid compact bone's microscopic appearance in thin sections and its response to weathering, because I was using published histological thin sections of human bone as reference specimens. Bovid diaphyses had an outer layer of lamellar bone under the periosteum, then alternate layers of fibrolamellar bone (Fig. 4.5). Next to the endosteal space was a layer of lamellar bone. Although this ultrastructural difference will usually not affect zooarchaeological inferences, Lipson and Katz's (1984) observation that, in terms of

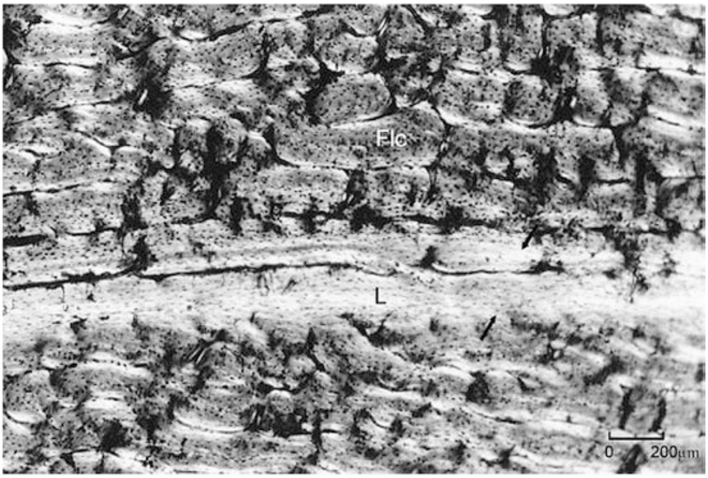

Fig. 4.5 Plexiform (fibrolamellar) bone structure, showing a growth layer in cattle (*arrow* indicating growth layer). *L* lamellar bone in growth layer, *Flc* plexiform (fibrolamellar) bone (From Cuijpers 2006:273, Fig. 4, used with permission of author and John Wiley & Sons, Inc.)

elasticity, plexiform bone behaved as an anisotropic material in one plane, whereas Haversian bone was uniformly isotropic, may be relevant to bone fracture studies. Awareness of it may also facilitate understanding and analysis of bones' response to weathering, heat, and other taphonomic processes that disrupt the histological structure of specimens.

4.5 Macroscopic Variants in Bone Architecture

As noted above, lamellar bone is the basic constituent of nearly all bone structures. *Compact*, or *cortical bone* has few spaces visible to the naked eye. It has lamellar or fibrolamellar bone on the outer and inner circumferences and densely packed osteons (secondary Haversian bone) within. Cortical bone may also be deposited in thin layers over the outer surfaces of cancellous bone tissue. *Cancellous*, or *trabecular, bone* is also composed of lamellar bone; however, it is characterized by large open spaces between its bony struts or trabeculae. This is often also called spongy bone. In adult animals, the trabecular spaces are filled with *red marrow*, the red-blood-cell-producing tissue, and fat. Cancellous bone lies under articular surfaces of long bones in vertebral bodies, in ribs, and in some other irregularly shaped bones (see below). Although the trabeculae of cancellous bone appear delicate, their arrangement actually provides very strong, strut-like reinforcement to the articulations, resisting high levels of stress so long as it is transmitted along orientations typical of the living animal.

Cortical bone covers cancellous bone at joint surfaces, lying in a kind of sandwich layer between the spongy bone and the layer of cartilage comprising the actual joint surface. These *subchondral* (under-cartilage) bone surfaces, once they lose their moist cartilage coverings postmortem, often develop a mosaic pattern of small cracks that give its smooth surface a distinctive appearance.

Cortical and cancellous bone types respond to stresses in different ways. Cortical bone resists stresses running in its normal plane of orientation in the living animal. However, it can fracture rather spectacularly through torsional stress such as that typical of skiing accidents, or as the result of dynamic loading, as with the impacts of great force in an automobile accident. Postmortem dynamic loading, as with the impact of a hammerstone, stresses the bone in an orientation it did not evolve to withstand. Thin layers of cortical bone over cancellous bone are readily abraded or flaked off, but in the living animal it is normally protected by soft tissue and cartilage, and hairline stress cracks are swiftly repaired. Cancellous bone seldom fractures under impact aligned along living planes of stress. Many generations of locomotion have selected for impact-resistant articular ends. Chapter 11 examines in detail how these intrinsic qualities of bone affect its postmortem fracture.

4.6 Growth and Development of Different Bone Types

Vertebrate skeletons develop and remodel with the types of cells and basic materials discussed above. Embryological research has shown two different pathways to bone formation in vertebrates. Some bones are formed in the cell layer that gives rise to skin; these are called *intramembranous* or *dermal bones*. They include bones of the cranium, the clavicle, the shells of turtles, and the scutes (armor plates) of crocodilians. Another type of bone is formed inside the body and is laid down on cartilage precursors; these are called *endochondral* (within cartilage) bones. They include the vertebrae and long bones.

Dermal bones of the cranium can also be used to determine age at death, since the joints between them, or *sutures*, close according to a time-sequenced schedule. In humans, this schedule is well documented and, in the best of cases, may allow rough age determination into the fourth or fifth decade of life. Ages of cranial suture fusion are less well known among other mammals.

Intramembranous bone grows directly in soft tissues, and its osteoblasts organize and produce bone without any precursors. Endochondral bone grows by replacing a cartilage "model," a process called *chondral ossification* (Tanner 1990). Two types of such ossification take place. The first deposits bone around the outside of part of an element (*perichondral ossification*). The second type forms by replacing cartilage from within the segment (*endochondral ossification*). Both processes can take place in one bone element, as can be envisioned in limb bones, which simultaneously grow in both girth perichondrally and length endochrondrally.

In mammals, long bones and other endochondral bones grow in a distinctive, three-zoned fashion. The central growth zone, called the *diaphysis*, ossifies peri-

Fig. 4.6 Tibia and fibula of a female northern fur seal (*Callorhinus ursinus*), showing recently fused proximal and fusing distal epiphyses with metaphyseal lines still clear (Photo by author of specimen from California Academy of Sciences)

chondrally; each long bones' end plates, or *epiphysis*, ossifies endochondrally. During the growth phase of the bone, the zone between diaphysis and the two epiphyses comprises the *metaphysis*, consisting of a cartilage plate constantly ossifying on its diaphyseal side and developing cartilage on the epiphyseal side (Fig. 4.6). Ossification entails invasion of the cartilage by blood vessels, development of osteoblasts, and deposition of bone behind the moving front of cartilage-forming cells. This pattern of bone growth allows substantial remodeling of the shape and prolonged growth as the bone elements are functioning and bones change in shape and proportions as an animal matures.

Mammalian endochondral bone growth thus involves a complex sequence of remodeling at the cellular level, with activation of osteoclasts, resorption from inner bone walls, and deposition of new bone all part of growth. Endochondral bone growth ends in fusion of epiphyses to the diaphysis through complete ossification of the metaphyses. Epiphyseal fusions in a given bone element do not occur simultaneously; some fusions take place well after the individual has reached sexual maturity. The schedule of epiphyseal fusions of various endochondral bones is reasonably well documented for modern humans and domestic animals (Silver 1963; Ruscillo 2006). These fusion times can be used to estimate the ages of younger animals, as will be discussed in Chap. 6.

4.7 Shape-Based Classification of Skeletal Elements

Because skeletal elements of similar shape have similar physical properties, anatomists and veterinarians have placed them into a few general shape categories. These are useful to zooarchaeologists because these forms have characteristic construction, associated nutritive tissues, and responses to mechanical and other types of stress. Thus, they may form functionally relevant categories when thinking about archaeofaunal assemblages. The most commonly used subdivisions are:

long bones: elements of roughly cylindrical shape, usually containing a large *medullary*, or *endosteal* cavity in which marrow and the endosteal connective tissue is located; in hoofed animals, the metacarpals and metatarsals are reduced in number and elongated, and are therefore classed as long bones;
short bones: elements of roughly the same dimensions in all directions, including carpals, tarsals, and phalanges;
flat bones: elements of roughly tabular form, with high ratios of surface area to volume, including the scapula, innominate (pelvic bone), ribs;
irregular bones: elements that do not fit into the above categories, including the cranium as a bone unit (although some individual cranial bones may be thought of as flat bones), vertebrae, patellae, etc.

4.8 Tissues and Features Associated with Bone

Various soft tissues are associated with, and several have been noted already in this chapter. Bones are covered with connective tissue called the *periosteum*. It is the source of perichondral bone growth, both under normal development and in response to injury. The *endosteum*, another bone-producing and remodeling tissue, lines the walls of medullary cavities. The articular surfaces of are covered with cartilage plates that do not ossify but remain as a smooth covering for the joint surface. *Red marrow* is found within adult cancellous tissue and also in the endosteal, medullary cavities of immature mammals. Red marrow produces blood cells and is the “marrow” referred to in discussions of bone marrow transplants. In adult mammals, the endosteal cavities contain a higher proportion of fat-rich *yellow marrow*, which varies in consistency and amount according to seasonal variations in the condition of the animal.

4.9 Composition and Histology of Teeth

Teeth are the only skeletal elements directly exposed to the environment. They serve primarily as food-processing elements but also are involved in prey acquisition, from the slashing teeth of sharks to the cropping incisors of cattle.

Teeth are composed of three substances: *enamel*, *dentine*, and *cement*. The enamel crown is the working part of a tooth and varies according to the dietary adaptation and sometimes the sexual dimorphism of a species. The hydroxyapatite crystals in enamel are larger than those found in bone (Lyman 1994:79). As those of us who have had the misfortune to chip or break a tooth know, enamel is harder but more brittle than bone and dentine. The latter comprises the inner cores and roots of mammal teeth, and it resembles bone in its proportion of collagen to bioapatite (see Chap. 7). It thus has considerable resiliency. In herbivorous mammals, wear of tooth crowns exposes dentine early in life, maintaining ridges of slower-wearing enamel and valleys of faster-wearing dentine over most of their life spans. This forms an efficient grating and grinding surface for silicon-rich foliage. Cement has an organic-to-inorganic composition similar to that of dentine, often lacks a cellular structure, and is deposited in and around teeth. In grazing species such as horses and African buffalo, the grinding surfaces of teeth are substantially enlarged by thick cement deposits around the tooth crowns.

Using uniformitarian assumptions, paleontologists and zooarchaeologists can often infer the feeding strategy of an animal species by inspecting its dental morphology. Mammals are distinctive among extant vertebrates in their heterogeneous collection of tooth shapes. This *heterodonty* appeared in mammal-like reptiles and in early mammals during the Mesozoic era. It facilitates several food-processing operations by progressively shifting the food around in the mouth. For example, a wolf's incisors and canine teeth seize the prey and inflict lethal damage, specialized pairs of premolars and molars then cut the prey's flesh up into chunks that can be swallowed, and the premolars and molars also can break down bones to obtain fat and marrow.

Mammals have two sets of teeth, milk or deciduous teeth and permanent teeth that erupt according to somewhat variable but broadly regular schedules in each taxon. This pattern of tooth replacement is called *diphyodonty*. As with epiphyseal fusions, patterns of tooth growth and development can serve as an index for estimating age at death. Wildlife biologists have also long used the time-sequenced patterns of tooth wear in herbivores, combined with the tooth eruption schedule, to estimate ages of animals, a strategy paleontologists and zooarchaeologists have emulated and elaborated.

Another aspect of tooth growth and development can, under optimal conditions, serve as an index of both age at and season of death. Dentine and cementum in the roots of the teeth build up over time. Best known are the grosser seasonal *incremental growth lines*, or *annuli*. These semiannual growth lines reflect good and poor nutritional cycles of the year in climates with marked differences in primary productivity because either warm/cold or moist/dry seasonality can strongly affect plant growth. Chapter 6 explains the use of these uniform processes of bone and tooth growth as they pertain to zooarchaeological age estimation.

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Chapter 5
Bone's Intrinsic Traits: Why Animals Eat Animals

Most archaeofaunal materials are subsistence residues. Human nutritional requirements and animal bodies' nutritional benefits set parameters for human's choices in acquiring animals for food. Some background in these generally uniform properties of living human and nonhuman animals helps zooarchaeologists grasp factors that underlie the prey choice and handling evident in archaeofaunas. This chapter deals with human nutritional "constants" and how zooarchaeologists began to use some of these to understand their assemblages.

Before reviewing this nutritional data, it is worthwhile to outline major shifts in hominin diet and continental expansion in relation to the expanded carnivory of the genus *Homo*. Human ancestors evolved in Africa, as did anatomically modern humans, *Homo sapiens*. Stable carbon isotopes indicate that, from four million years ago, multiple species of African hominins shifted from the C_3 diet typical of common chimpanzees (*Pan troglodytes*), to one emphasizing C_4 plants, tropical grasses or sedges of African wetlands. This shift coincides with expansion of grassland habitat in Africa. Stable carbon isotopes cannot distinguish between the consumption of C_3 and C_4 plants and the eating of animals that consumed such plants. Early *Homo* shows more dietary diversity than some other hominin species, with a mix of C_3 and C_4 sources. The earliest flaked stone tools are well dated to 3.3 million years ago (Harmand et al. 2015); the earliest widely agreed upon evidence of stone tools marks on animal elements dates around 2.5 million years (Domínguez-Rodrigo et al. 2005). Claims for cut marks at nearly 3.4 million years remain controversial (McPherron et al. 2010; Domínguez-Rodrigo et al. 2012). The genus *Homo* is thus descended from omnivores that, from around 2.5 million, engaged increasingly in acquiring larger vertebrates for food, as evidenced by bones with cut marks and hammerstone traces at multiple sites in eastern Africa around 2.0 million years ago (Braun et al. 2010; Domínguez-Rodrigo et al. 2010). *Homo erectus* emerged slightly less than two million years ago in Africa, with individuals on average larger in brain and overall body size than earlier species. Some attribute these traits and the species' successful dispersal into tropical and temperate Eurasia about

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1.7 million years ago (Antón 2003), to increased input of animal foods (Klein 2009), others to using fire to prepare plant foods (Dominy et al. 2008), still others to a combination of pyrotechnology and new social arrangements among adults (Wrangham 2009). This 1.7 million year date also coincides with the estimated time of that a tapeworm of the genus *Taenia* that originally had a life cycle only in large African carnivores and their prey species diverged from its parent population to permanently parasitize hominins (Hoberg et al. 2001). *Taenia*'s life cycle depends on sustained predator-prey relationships, this suggests that, regardless of how they obtained larger animal bodies, hominins did so regularly. *Homo erectus* apparently adapted well to temperate climates, though their ability to live in with extreme cold situations appears not to have equaled that of later hominins such as Neandertals (Gamble 1986).

Anatomically modern humans dispersed from Africa into Eurasia, New Guinea, and Australia around 75,000 years ago (Pagani et al. 2016; Mallick et al. 2016; Malaspinas et al. 2016). *Homo sapiens* occupied arctic latitudes during an ice age, where animals comprised most available food, over the last 45,000 years (Fu et al. 2014; Pitulko et al. 2016). Competence living in such biomes facilitated entry into the Americas during or at the end of the Last Glacial Maximum, 25,000 to 15,000 before present. Humans' increasing densities and more intensive interactions with certain animal species, notably the dog, in the late Pleistocene, evolved into multiple, independent animal and plant domestications in Eurasia, Africa, and the Americas in the Holocene, enabling unprecedented population growth and emergence of entirely new forms social relations.

Anatomically modern humans' success is often ascribed to increasingly complex animal acquisition techniques and technologies such as projectile weapons, nets, and traps, as well as language and extensive, exchange-mediated social networks (Klein 2009). One could also argue that technological advances in handling plant and animal foods to facilitate storage underwrote much of human expansion, both in glacial epochs and in the later coevolution of humans and mutualist species that we call domestication. Much of this book is devoted to the signatures of different methods of handling vertebrates preserved in archaeofaunas.

5.1 Nutritional Needs Met by Animal Foods

This section outlines the contribution of each to human wellbeing, our species' ability to store each in the body, and alternative sources of these nutrients. One can see these as uniformitarian traits of animal bodies that reward humans who incorporate them into their diets and thus as very relevant to zooarchaeological inference. Animal foods are usually high in proteins, fats (varying according to taxon), calcium, iron, and Vitamins A, B_1 (thiamin), B_2 (riboflavin), and C.

5.1.1 Protein

Proteins are composed of amino acids, the building blocks of tissues in the body and the precursors to antibodies, enzymes, and some hormones. Proteins also supply energy: one gram of protein supplies about 4 kcal of energy. Extreme protein deficiencies can lead to marasmus and kwashiorkor, diseases normally found only in famine conditions, or among the very poorest persons in generally low-protein-intake agricultural groups (Robson 1972).

Estimates of the amount of protein needed to maintain tissues and body function in adults vary by nation and their habitual levels of protein intake, but 50–75 gm per person per day supplies more than an adequate amount (Keene 1985:182). Severe protein deficiency in female mammals during pregnancy and lactation can produce Type 2 diabetes, hypertension (high blood pressure) and heightened risk of early stroke or heart failure in their offspring, as was discovered in longitudinal studies of children of Second World War famine victims (Barker et al. 1993; Langley-Evans et al. 1996; Godfrey et al. 1994). Effects of prenatal protein deficiency cannot be remedied by nutritional supplementation after birth. Grains and legumes supply an alternative form of protein, but these carbohydrate-rich foods do not appear to have been eaten in quantity until around the emergence of farming.

5.1.2 Fats

Fats can be derived from animal or vegetable sources. They are concentrated, relatively readily digested sources of energy, supplying about 9 kcal of energy per gram. Ingested fats are broken down in the gut, absorbed, and restructured into lipids essential to nutrient transport. They carry fat-soluble vitamins A, D, E, and K and other nutrients from the gut into the body's circulatory system where they can be used or stored in organs or fat.

Animal fats are notoriously rich in cholesterol, which has a bad name in the popular literature because of the link proposed to atherosclerosis in modern, fat-rich lifestyles. Cholesterol is in fact an essential precursor to acetylcholine, a neurotransmitter, to Vitamin D (which is essential in bone deposition), and to various hormones, including steroids or sex hormones (Scrimshaw and Young 1976).

Disagreement exists among nutritional researchers over how much fat is needed in the human diet. Bunn and Ezzo (1993) have argued that earlier hominins' need for fat approached that listed in the U. S. Department of Agriculture standards for fat per adult per day, thus motivating increased foraging for animal carcasses, confrontational scavenging, and finally hunting in Plio-Pleistocene times. Sept (1994) points out that the U.S.D.A. standard may be double what most humans need to remain healthy. However, extremely low-fat diets, especially if high in protein, can set into motion physiological processes leading to weight loss, illness, and even starvation, as will be seen below.

5.1.3 Essential Fatty Acids

Plant and animal fats also contain certain amino acids involved in cell membrane structure and function that are precursors to prostaglandin compounds that regulate smooth muscle and gastric function and the release of hormones (Scrimshaw and Young 1976; Garza and Butte 1986). The human body produces a range of fatty acids through its own fat metabolism, but it cannot synthesize others, without which the body cannot function and grow. These aptly named Essential Fatty Acids (EFA) are most commonly found in vegetable fats but are also present in fatty meats.

The Essential Fatty Acids are further classified into omega-three and omega-six fatty acids, according to their chemical structure. Omega-three EFAs include alpha-linoleic acids, stearidonic acid, EPA and DHA. Alpha-linoleic and stearidonic acids are commonly found in nuts, seeds, plant oils, and green leafy vegetables, while EPA and DHA are common in oily freshwater and sea cold-water fish. Omega-six EFA include linoleic acid, highly concentrated in various nuts and in oil seeds, such as olive, canola, almond, sunflower. Omega-six EFA gamma-linolenic acid is found in some seeds, and arachidonic acid is present in meat and animal products.

Humans can store EFA in their own fatty tissues, and persons in seasonally variable ecosystems can build up a surplus when vegetable foods bearing them are common, and later tap their stored supply when they are lacking. Seasonal shortages of EFA seldom have serious effects on adults, who can mobilize the fatty acids stored in their own substantial adipose tissues (Speth 1983). However, modern medical studies indicate that infants of malnourished mothers may be especially vulnerable to effects of EFA deficiency (Innis 2007). Pregnant and lactating females mobilize cervonic and linoleic acid from their fat depots to build fetal and infant neural tissues. Deficiencies of linoleic acid can lead to skin lesions, problems with the body's water balance, susceptibility to infection, and in immature individuals, impaired growth.

Sept (1994) argued that, under most circumstances, early hominins in tropical Africa would not have had to resort to predation or scavenging to obtain essential fatty acids and protein. These are seasonally available from plants in riparian and bush habitats in quantities sufficient to fulfill adult recommended daily allowances (RDA). Moreover, EFA from these sources could be "banked" in adipose tissues for seasonal shortfalls. Nonetheless, heightened maternal need to supply pre- and post-natal EFA to developing offspring would apply in all environments.

Modern cases demonstrate that it is possible to live on a nearly exclusively vegetarian diet, as do a number of agricultural groups in the world today (Lappé 1982). If one becomes a vegan and excludes domestic animal products such as milk products and eggs, risks include impacts of protein, vitamin B_{12}, essential fatty acid deficiency on neural development and maintenance (Bourre 2006). Vegans depend on the present-day world food system, long-distance transport of ecologically disparate foods and smoothing of seasonality, to sustain their nutritional health. For humans in less developed and integrated economies most consumption of animal products is a simple means of fulfilling basic needs for protein, fat, and EFA.

5.1.4 Minerals

In today's world food system, nutritionists recommend consuming dairy products, dried legumes, and green leafy vegetables as concentrated sources of calcium (Scrimshaw and Young 1976). All these foods are domesticated products, and, with the exception of the last, would have been either unavailable or available in very low quantities in pre-agricultural times. Wild green leafy vegetables would have only seasonally available. Although it has lower calcium concentrations than do these domesticated plant foods, meat constitutes a year round calcium source.

Iron is essential for production and maintenance of red blood cells, protection of other tissues, and enzymes involved in energy metabolism and is essential to fetal neurological development (Bourre 2006). Today it can be obtained from eggs, legumes, whole grains, and green leafy vegetables, as well from lean meat (Scrimshaw and Young 1976). Again, imagining times before agricultural systems, animal bodies probably were a major, year-round source of iron for much of hominin evolution, especially in temperate regions.

5.1.5 Vitamins

Vitamin A is a fat-soluble vitamin essential for the development of visual pigment and maintenance of the epithelial tissues. It plays a role in synthesis of mucopolysaccharides, a constituent in cartilage and other tissues. Beta-carotene, or Provitamin A, is a Vitamin A precursor found in green vegetables, which can be converted into Vitamin A by the body (Scrimshaw and Young 1976). Vitamin A in its complete form exists in animal foods and is richest in milk products. It can be stored in body fat. In pre-agricultural times, when vegetable sources were probably strongly seasonal and dairy sources unavailable, meat and fat would have been a consistent source of Vitamin A throughout the year. Humans can overdose on Vitamin A if they consume the liver of a top carnivore, which concentrates the vitamin. Hypervitaminosis A causes skin disruptions, anorexia, vomiting, and inflammation of bones' periosteum, with concomitant rapid woven bone growth around shafts, and death.

Vitamin B_1, or thiamin, is a water-soluble compound, involved as a co-enzyme (thiamin pyrophosphate) in metabolism of amino acids of both plant and animal origins (Keene 1985; Scrimshaw and Young 1976). Thiamin is essential to the efficient mobilization of energy from fats and carbohydrates. Its deficiency causes beriberi, a syndrome involving nerve damage, edema, and heart failure. Because thiamin is widely distributed among plant and animal foods, meat does not comprise a special source, except in zones with extreme winters, when plant food are absent.

Vitamin B_2, or riboflavin, is another water-soluble vitamin common in plant and animal tissues. It also is involved in the formation of two flavinoid coenzymes that facilitate efficient metabolism (Scrimshaw and Young 1976). Deficiencies can cause lesions in epithelial tissues of the skin and eyes. Prior to the emergence of domestic plant species and the modern world food system, animal foods assured year-round access to riboflavin.

Vitamin C, or ascorbic acid, is most abundant in plant foods such as citrus fruits, peppers, tomatoes, and greens, but it is present in meat. By maintaining the intercellular matrix, ascorbic acid is essential in the maintenance of bone, dentine, and cartilage. It is a key constituent in collagen synthesis. Scurvy, the ascorbic acid deficiency disease, involves degeneration of skin, blood vessels, and gum tissues supporting teeth.

5.2 Demands Above the Norm: Gestation, Lactation, Early Childhood

Published nutrition standards are usually based on adult and, at least formerly, male physiological needs. However, reproducing females and their offspring undergo intense, nutritionally based selective pressures hidden by adult average data. Scrimshaw and Young (1976: 56) note that investigators have tended to regard infants and young children as little adults and, with a small allowance for their growth, to extrapolate their requirements proportionately by weight from studies of older individuals. This approach does not take into account changes in the metabolic activities of cells and in the rates of turnover with age (Garza and Butte 1986).

Nutrient demands of developing mammals, and, by extension, on the supplier of their nutrient needs, the pregnant and lactating mother, differ from those of adults. Most brain growth, development of other neural tissues, and much skeletal and muscular growth occurs either during lactation or in the post-weaning phase of early childhood. It is important to recall that in most traditional pre-agricultural and agricultural societies, mother's milk supplies nearly all a child's nutrition for the first 2–4 years of its life (Dettwyler 2004:717–719).

5.2.1 Calcium

Prenatal maternal nutrition affects an infant's later growth and health status. A mother's body can supply adequate levels of calcium and lipids by mobilizing bone mineral and fats stored in her body. As noted in Chap. 4, through hormonally mediated mechanisms, pregnant females may increase absorption rates of dietary calcium to replace the mineral being mobilized to build fetal tissues. In case of severe dietary shortages, calcium continues to be mobilized from maternal bone, to the detriment of the mother's long-term calcium budget (Fedigan 1997).

Lactation imposes even greater demands for calcium on the nursing mother than pregnancy because much skeletal growth takes place during this span. Laboratory studies of rats have shown that as much as 25% of calcium can be mobilized from thigh bones of rats during the normal lactation span. In human females, primary losses of bone occur in the trabecular areas of long bones, as they do in lactating laboratory animals (Fedigan 1997).

5.2.2 *Childhood, Protein, and Essential Fatty Acids*

Protein requirements from in the first year of life are more than twice that of an infant over 1 year of age, and over four times that of a young adult and (Scrimshaw and Young 1976:54). Human brain growth patterns convey a sense of the nutritional demands upon human females during lactation: at birth, a human infant's brain is about 25% of adult size; over the first 6 months of life, its brain doubles in size. Children achieve all but 10% of their brain growth by age five and all but 5% by age ten (Tanner 1990:104). During brain growth, children require constant and relatively high levels of proteins, cholesterols and related lipid substances, and EFA, especially linoleic acid. In societies without milk animals, all but 10% of brain growth takes place before weaning, when breastmilk supplies nearly all of these requirements. Nursing infants and very young children therefore exert a tremendous demand on the maternal body. These facts are recognized in nutritional tables for pregnant or lactating human females (see Scrimshaw and Young 1976: 60–61 for adaptation of FAO tables).

A human infant's nutritional dependency on mother's milk is much longer than in most mammals, requiring several years of good-quality maternal nourishment, or storage reserves. Human milk is not a "high-energy, high-quality" food source in comparison to milk of many other mammals. It is low in energy per unit volume and low in milk solids, resulting in slow growth and development rates compared to those of many placental mammals (Garza and Butte 1986; Oftedal 1984; Stini 1980). Davis et al. (1993) demonstrated that human, common chimpanzee, and gorilla milk share the same protein make-up, reflecting a long evolutionary history. Mothers can slightly increase the proportions of proteins and fats in their milk, as well as the volume and calorie levels, by maintaining their own intake of high quality foods.

The key to female reproductive success is thus not simply meeting average daily individual requirements but storing and mobilizing EFAs and other proteins for their maximum, sex-specific needs of supporting infant growth and development, in the face of variations in seasonal resource availability. This is especially true in areas with shortened plant growing seasons, where animal foods may be more important sources of such nutrients. Zooarchaeologists therefore need to consider how these demands may structure foragers' decisions in acquiring animal foods that supply many of the exceptional nutritional needs of pregnancy and lactation, without which the species cannot survive.

5.3 Coping with Seasonality

All members of the genus *Homo* entering temperate and colder zones faced novel dietary challenges. Some solutions were inherent to the physiology of their taxon. Even in tropical latitudes, foragers and subsistence farmers diverge from the "steady state" of food-intake that prosperous populations in the contemporary world food system take for granted. Because certain plant and animal foods are available only at given times of the year, they eat in a more seasonal pattern, with variations in caloric intake as well as specific foods (Lee 1979; Peters et al. 1981; Sept 1990). In times of food shortfall, people live off fat stored in times of abundance, breaking down fat to access calories and fat-soluble vitamins and minerals. Thus, genus *Homo* entered temperate zones with a physiology that permitted it to survive times of low food intake. Yet seasonality in temperate, subarctic, and arctic zones poses much greater challenges. During long seasons of frost, edible plants stop growing altogether, calling for further coping tactics, either somatic or extrasomatic.

Among vertebrates, several options have evolved to cope with overwintering through the non-growing season. Some insects, many birds, and some mammals migrate to warmer zones, a strategy that imposes its own energetic costs and dangers. Migration also removes prey biomass from the reach of carnivores remaining in the cold zone. Another strategy involves dropping into torpor – hibernating – through part of the winter. As with migration, this represents major physiological challenges and requires a resting place inaccessible to predators that could attack during torpor. Fishes, amphibians, and reptiles cope with freezing conditions physiologically, tolerating deep chilling of their tissues. Hibernating bats, bears, certain rodents, and other placental mammals drop their metabolic rates and live off stored fat, which requires accumulating enough body fat not only to survive the winter in torpor but also to forage in spring. Female bears sustain the added energetic costs of birth and lactation while hibernating. Only a few high-latitude terrestrial mammal species (Lefèvre 1997) build up enough fat to hibernate, but all must lay down a seasonal fat deposit. Deer and most other hoofed animals, many rodents, various cat species, mustelids, and raccoons accumulate deposits of fat in the summer and autumn and use it to stay warm and actively forage during the winter.

As with other animals, humans must cope with higher latitude challenges well enough to rear offspring to adulthood. Humans readily build up extra adipose tissues, and populations living in strongly seasonal regions appear especially inclined to add fat (Pond 1997). For much of human history, seasonal fattening followed by weight loss in "lean times" was normal among foragers, pastoralists, and farmers, especially those in agriculturally marginal environments. The body is the most efficient place to store food reserves: no one can steal it, and animal pests can't spoil it. In cold climates it insulates and is a ready source of metabolic fuel. As noted above, fat stores vitamins A, C, E, and K and EFA when these are abundant, tapped when diet does not supply levels essential to body function. In a significant number of people in high-latitude populations, shortening day length provokes a lowering of metabolic rate and mood, called seasonal affective disorder (SAD), one symptom of which is craving for carbohydrates and weight gain (Rosenthal 1998). Today, SAD is viewed as a public health problem, given its risks of depression and even suicide. However, it may reflect an older adaptation to seasonal food shortage. Anatomically modern humans combine such somatic adaptations with technologically mediated food storage and long-distance exchange relations to avoid the worst risks of seasonal food scarcity, especially for infants and children.

5.4 Problems of Meat-Rich, Carbohydrate-Poor Diets in Humans

Humans are basically omnivores with some leaning toward carnivory. Truly carnivorous mammals' physiologies build and maintain their bodies and those of their offspring by eating other animals. However, humans cannot live for long exclusively on lean meat, which without carbohydrates produces deleterious physiological reactions. In recent times carbohydrate-poor diet was mainly a risk for higher-latitude groups undergoing long cold seasons, with few storable plant foods available during summer. However, during Pleistocene glacial cycles, roughly similar temperatures would have affected groups in what are now the temperate latitudes of Eurasia and the Americas. In a landmark paper, Speth and Spielmann brought together knowledge of human physiological needs, ethnography, and zooarchaeology to explore motivations for prey species and body-segment selectivity among such groups, as well as other, technological and socially mediated tactics for coping with this problem.

5.4.1 Specific Dynamic Action (SDA) Effects

Using data from metabolic studies of humans and other mammals, historic records, and ethnographic information, Speth and Spielmann outline the energetic and physiological costs of relying very heavily on animal foods. Breaking down any ingested tissue during digestion requires energy expenditure, and protein is the most energetically expensive. Amino acids from lean meat must be broken down into glucose and other by-products via the citric acid cycle (Scrimshaw and Young 1976), and the glucose must then be converted to adenosine triphosphate (ATP) in the tissues, another energetically expensive process. The *specific dynamic action* (SDA) statistic calibrates these trade-offs, expressing, as a percent, a food item's energetic costs (see references in Speth and Spielmann 1983:5). A largely carbohydrate intake has an SDA of about 6%, that is, for each 100 calories carbohydrate ingested, 6 calories of these will be spent breaking it down. Fat SDA runs 6–14%, whereas for a predominantly protein diet, the SDA runs as high as 30%. Speth and Spielmann (1983:6) cite studies of Inuit who ingested traditional meat- and fat-rich diets, plus self-administered experiments by Arctic explorers of European ancestry, indicating that, with such diets, a person's basal metabolic rate (BMR) increases 13–33%. The leaner the meat ingested, the higher the SDA effect because no fat offsets protein SDA.

The consequence of such a raised BMR is the need to consume even more calories to meet BMR and activity-based energy needs. The cycle continues if subsequent calories are also lean meat. This may account for explorers' accounts of North American Plains Indians and Inuit consuming kilograms of meat at a sitting. Speth and Spielmann quote Shepard as estimating that an active Inuit male might need to consume 3600 calories in a 24-h period, and if these calories were from lean meat, between 3.4 and 3.6 kg would have to be eaten. A shift in diet toward more carbohydrates lowers BMR levels, as demonstrated by Arctic explorer research (Speth and Spielmann 1983:6).

Speth and Spielmann argue that terrestrial ungulates in temperate to Arctic zones become fat-depleted in the late winter and early spring months, having exhausted their adipose reserves while surviving on sparse forage. People eating such lean animals risk having to increase their overall calorie intake just to break even, in a season when their own bodies were also fat-depleted.

5.4.2 Effects on Body Tissues and Protein-Sparing Effects of Carbohydrates and Fats

The untoward effects of a lean meat diet do not stop with raised BMR. With such a dietary regime, the body's physiological priorities put its own protein-based tissues at risk. Under-supply of amino acids, and hence glucose, from food will cause the body to attack its own muscle and organ tissues to produce energy. Dietary carbohydrates and fats intervene in this destructive cycle, with glucose production redirected to the carbohydrates and fats. Carbohydrates have been established as more efficacious than fats, per unit calorie administered, in reducing the breakdown of the body's own proteins for energy.

5.4.3 Other Effects of Dietary Fat Shortage and High Protein Intake

A high-protein, low-fat diet inhibits absorption of calcium, perhaps because fat-soluble Vitamin D is not present to transport calcium across cell. Inhibition of calcium uptake during seasonal fat shortages could lead to bone loss or retarded bone deposition. These problems would be especially acute for infants and children in the process of skeletal growth, nursing mothers mobilizing calcium for milk, and post-menopausal women with calcium budgets already unbalanced by the hormonal changes.

5.4.4 Tactics to Cope with Seasonally Lean Meats

Speth and Spielmann (1983:19) contend that seasonal, fat-to-lean animal intake in environments with scarce carbohydrates may drive "lean season" hunting toward prey with high fat, rather than caloric, returns. Beavers, waterfowl, and some fishes are fat-rich, offering the fat needed to supplement lean meats from hoofed mammals.

Another strategy known from ethnographic cases is storing fat- and carbohydrate-rich foods for consumption with lean meats during the seasonal minimum. Rendering body fat from mammals, birds, and fishes, simmering bones to extract bone grease, and drying oily fish all produce storable fatty foods for winter and early spring consumption. Pemmican, the legendary traveler's food among Plains Indians, is a compound of dried lean meat, rendered fat, and dried berries. It brings together the ingredients essential to sustaining health.

Finally, ethnographic and historic records testify to trade for fat- or carbohydrate-rich foods, as was the case in Plains-Pueblo trading relations, where bison hunters obtained maize and other agricultural produce in exchange for meat and hides. Inland and coastal Athabascan Indians in the Northwest of the U. S. and Canada exchanged furs from inland animals for rendered oil of seals, whales, or of the smelt-like eulachon fish (*Thaleichthys pacificus*).

5.5 Body Segments and Nutrition: Not All Parts Are Equal

Skeletal elements simultaneously play protective, biomechanical, and nutrient reservoir roles in living animals, with different elements playing disparate roles in the body. As a result, these are differentially attractive to animal consumers and are variably durable under consumption. Some bones are reservoirs of nutrients such as red marrow and yellow marrow. Others, such as the skull and vertebrae, enclose appetizing neural tissues. Any consumer able to breach bony structures to access their contents will target those elements.

At the same time, because they have distinct biomechanical functions, different skeletal elements possess variable densities of bone tissue per unit of volume, or *bone mineral density* (BMD), which affect an element's response to the impacts of consumers. Some elements, or segments of them, give way, while others do not. Thus, the uniform qualities of bones related to their life functions determine how carnivores, including humans, attack them and how the bones respond. For example, carnivores, regardless of whether canid, felid, or hyenid consume large prey carcasses in a remarkably uniform sequence of anatomical zones. This consumption sequence, discussed in more detail in Chap. 12, represents carnivores' trade-off between prioritizing the nutrient-richest segments and their ability to access those nutrients, given the variable resistance of the skeleton.

In *Nunamiut Ethnoarchaeology* (1978) and in *Bones: Ancient Men and Modern Myths* (1981), Binford attempted to standardize previously intuitive assessments of the relative food values of different sections of mammal carcasses. He ranked skeletal elements in order of their associated soft tissue "utility" to humans, using four different scales: meat, marrow, bone grease utilities, and then a combined general utility index. Binford's goal was to establish uniformitarian principles for assessing the "logic" of larger animal butchery, as well as of body segment discard or transport by hunters and to apply this approach for analyzing archaeofaunas. Binford's approach can be condensed as follows: the presence or absence of bone elements with specific associated nutritional values in an archaeological site reflects their deliberate selection or abandonment by ancient hunters. Frequencies of elements of different nutritional utilities in turn allow us to assess the nature of the site, for example, a kill/butchery locale versus a residential site. Efforts to build uniformitarian frameworks for evaluating frequencies of elements will be detailed in Chaps. 20 and 21.

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Chapter 6
Bone's Intrinsic Traits: Inferring Species, Sex, and Age

All physical traits zooarchaeologists use to infer taxon, age, and sex in vertebrates emerge in life through the interaction of animals' genetics with their environment. Such traits are amenable to actualistic study and relational analogies, because most are linked to fundamental functional complexes of feeding, locomotion, and reproduction, and because they develop and function in predictable ways. Chapter 3 outlined how and why paleontologists or zooarchaeologists assign fossil bone specimens to species or other taxonomic classifications, based on their morphology. Likewise, certain physical attributes of vertebrate skeletons permit zooarchaeologists to identify or estimate body size, sex, and ages at death, given the generally uniform processes of growth and development. Some of these sexually specific features, such as antlers, grow in a seasonal pattern and can be used, with circumspection, to estimate the time of year they are acquired. Annular growth patterns in fish bone or mammal teeth can be used to estimate age at death, and season of death can sometimes also be inferred (see below).

The strong causal and functional linkages of such osteological traits make them sound building blocks for drawing more complex inferences about how people interacted with animals in the past. For example, did hunters focus mainly on reindeer, and why? Was more than one breed of horse present at this Roman frontier town? Did Neanderthals acquire adult animals in their prime as efficiently as did the anatomically modern human hunters who succeeded them in Europe? Did the herders at this encampment cull most immature males from their herds, but allow females to live and reproduce until a ripe old age? Was this site used only when the salmon ran in the nearby river or for a longer span of time during the year?

Despite strong causal relations between these traits and processes responsible for them, they still present interpretive problems. Animal populations encompass considerable inter-individual variability, often expressed in the time of development of individuals' sex- and age-related traits. In making such determinations, zooarchaeologists often benefit from research by zoologists and ecologists. Wildlife management studies of the relation of age to body size and methods of age estimation in modern populations can serve as actualistic datasets from which zooarchaeologists

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can base their inferences about ancient individuals from the same species. Often, however, zooarchaeologists find themselves working with species or body segments that have never been well-studied actualistically. In fact, zooarchaeologists have contributed to ecology and zoology by defining ages of tooth eruption and epiphyseal fusion in wild animal populations.

This chapter and Chap. 7 review the voluminous literature on determining species, size, sex, and age in mammals from their skeletal remains, highlighting major analytical tactics, classic and informative sources, and ongoing controversies. This chapter begins with species identification and then surveys size estimation and sex determination. Simply because the literature on age determination from teeth is so extensive, it is placed in a separate chapter, which will also address the question of precision and accuracy of all estimates in inherently variable biological populations. As other chapters, these two chapters do not attempt a comprehensive bibliography; rather, they refer readers to portals into that rich literature. Two key works in English that offer entry into this rich literature are Wilson, Grigson, and Payne's (1982) *Ageing and Sexing Animals from Archaeological Sites* and Ruscillo's (2006) *Recent Advances in Ageing and Sexing Animal Bones*.

6.1 Taxonomic Determination

Zooarchaeologists undertaking taxonomic identification from bone specimens can build on nearly four centuries of comparative anatomy and paleontology, including an illustrated literature on identification of various groups, as well as a methodology for initiating comparative research. Guides to osteology are part of that tradition, emphasizing morphological traits that set one taxon apart from closely related ones. From the 1930s, zoologists and paleontologists began supplementing purely qualitative prose descriptions and drawings with measurements to specify the small differences in proportion of closely related species' bodies and bones.

Like zooarchaeologists, paleontologists lack the skins and soft anatomy that zoologists use to distinguish extant animal species. As a consequence, their research has focused on preserved hard parts. They have developed systematic methods to approach the comparison and taxonomic identification that can guide zooarchaeological analysis, including threshold criteria for taxonomic identification to the generic or higher level rather than the species, and for documenting novel or difficult species identifications in initial site or monographic reports. Informative discussions of how these methods apply to zooarchaeology have been offered by Lawrence (1951), Driver (2011), and Lyman (2011, 2005), and excellent examples of osteometric comparisons in zooarchaeological research exist (Peters 1986a, b; Grayson 1988). However, as Driver and Lyman stress, this time-honored, systematic approach is not as pervasive in zooarchaeology as it should be. These procedures are especially important to review now that most prospective zooarchaeologists are trained in stand-alone courses in many departments of anthropology or archaeology, rather than studying directly with zoologists or paleontologists, as did most of the first cohort, where exposure to that literature was part of their training. A good example of such paleontological methods can be found in Barnosky (2004).

Today, DNA analysis is an increasingly affordable tool for tracing biogeographic and evolutionary histories in zoology, paleontology, and zooarchaeology. Zoologists regularly have used DNA analysis to sort out relationships of living taxa. For example skunks and their relatives have been placed their own zoological family, the Mephitidae, separate from the Mustelidae, in which they were formerly grouped with weasels, otters, wolverines, and ratels (Dragoo and Honeycutt 1997; Flynn et al. 2005). Given that these changes are ongoing, zooarchaeologists should stay current with the literature for geographic areas and taxa with which they work (Bovy 2011). Not all archaeofaunal specimens preserve sufficient ancient DNA (aDNA) for analysis, nor can zooarchaeologists afford to employ this as a standard identification tool. However, aDNA analysis has been used to distinguish species when neither morphology or measurements could do so, as in the case of fragmentary whale bones from sites on the northern Oregon coast of North America (Wellman et al. 2016). It was also used to check size-based identifications of cottontail (*Sylvilagus*) versus jackrabbit (*Lepus*) specimens in U.S. Southwestern archaeofaunal samples, with interesting results (Yang et al. 2005). Analyses of modern domestic animals' genomic variation, combined archaeofaunal specimens' aDNA, have revolutionized animal domestication research (see Chap. 23). As these examples imply, time-honored species identification methods are nonetheless the bedrock upon which samples for such analyses rest.

Another recently applied molecular biological method of taxonomic characterization currently less expensive than aDNA analysis is protein mass-fingerprinting from collagen (PMF), see Thiede et al. (2005). Originally developed and applied in biomedical studies, the technique's standardization, automation, and computer-based analysis permit swift analysis of taxonomically distinctive peptides in collagen. Its application to has been called Zooarchaeology by Mass Spectrometry or ZooMS (Richter et al. 2011). The method can differentiate samples at the familial level, as it did in Richter et al.'s study of fish peptides, and sometimes at the generic level, as it did in Buckley et al.'s (2010) analysis of sheep vs. goat peptides. One of its most interesting applications to date was to hair combs fashioned from deer antler in three Viking workshops around the far eastern North Sea and western Baltic (Ashby et al. 2015). Manufacturing processes in the workshops had substantially reduced chances of visually identifying most specimens' taxon. Peptide analysis revealed presence of local deer, undifferentiated by this method between red deer (*Cervus elaphus*) and elk/moose (*Alces alces*), and of reindeer (*Rangifer tarandus*), which were not native to the terrestrial hinterlands around these Viking settlements. From these results, as well as "traditional" zooarchaeological identification of reindeer antler in another such settlement to the south, the authors develop an argument that Viking settlements possessed overseas "hinterlands," mediated by extensive commercial seafaring, for which some documentary evidence exists.

6.1.1 Illustrations Versus Comparative Specimens

Nearly every guide to species identification of skeletal elements presents photographs or drawings of the elements. The best such guides offer multiple views of an element and indicate its species-specific, distinctive features. Some may also present measurements of elements previously shown to exhibit key metrical differences between two or more species (Lyman 2005). Many zooarchaeologists working in the field carry binders or digital tablets with images of skeletal elements from the species that we might have trouble distinguishing. My personal identification notes include illustrations from classic sources, my own drawings and photos, tables of suture and epiphyseal fusion ages for various species, photos of bone modifications from other researcher's and my own work, weathering stage criteria, and other useful references.

As implied above, zooarchaeologists are not only consumers but also producers of specimen illustrations. I urge my students to sit and draw bones as a way of learning morphological detail of different species, even if they consider themselves to be terrible artists who produce ugly little sketches and would rather photograph with their smart phone. Drawing requires a person to look long and hard at a specimen, and that is the real benefit. Once the image is committed to one's visual cortex, the drawing and notes on it may be more mnemonic devices than the actual means of identification.

However, drawings of bones are no substitute for actual comparative specimens. One zooarchaeological corollary of Murphy's Law is that the fragment of an element being examined is from the only part not illustrated in the identification guide. At the end of a particularly long day, I have actually caught myself trying to rotate a drawing, to see if that part of the bone would come into view. Three-dimensional scanning technology actually *does* permit a researcher to "rotate the illustration," although those currently available do not yet encompass the inter-individual variability with a species, by sex, age, or geographic region. Such aids are much better than nothing, but comparative collections in natural history museums or other collections are nonetheless essential when working with some cases of species identification (Lyman 2010).

6.1.2 Bone Measurements

To use size and morphology to determine species, to estimate body size (see next section), and to describe precisely the morphological differences between male and female (see **Sex Determination**), bone elements are measured. Morphometrics have been used not only to describe the shape of skeletal elements but also to infer from these animals' locomotor patterns and, by extension, foraging adaptations (e.g. Plummer and Bishop 1994).

The basic requirement of metrical data collection is that it be accurate, replicable, and made at commonly agreed-upon locations on an element. The classic guide

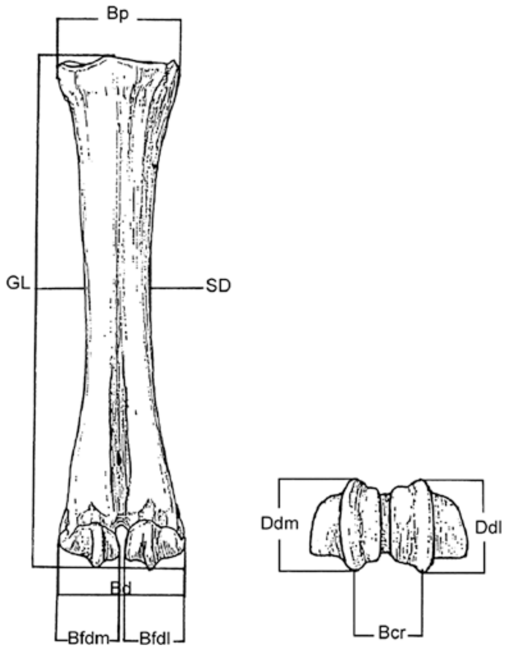

Fig. 6.1 Template for measurements taken on domestic cattle metapodials, from Telldahl et al. (2012:123, Fig. 2). (Drawing by the senior author with Bp, GL, SD and Bd measurements after von den Driesch (1976) and the BFdm, BFdl, Ddm, Ddl and Bcr after Duerst (1926), used with permission of senior author and Elsevier)

for measurements that fulfills these criteria for mammals is Angela von den Driesch's (1976) *A Guide to the measurement of animal bones from archaeological sites*, in which illustrations show the placement points for measurement of axial and appendicular skeletal elements in a wide variety of mammal species (Fig. 6.1). Each measurement is named by an abbreviation of its anatomical placement and type. Others have emulated this template for species not included in von den Driesch's volume (e.g. Etnier 2002).

Measuring is normally accomplished with vernier calipers, either manual or electronic, and the latter can be linked directly to a digital database. Other devices include the bone-measuring box, standard in human osteology. For very large specimens, one may resort to spreading calipers or to a large measuring tool known in physical anthropology as an anthropometer, as my colleague Josh Snodgrass did in our study of pinniped osteology, in which case it was, briefly, a pinnedometer. To measure micromammal elements, Donald Grayson (personal communication, 1978) used machinists' micrometers, usually employed on very small mechanical parts.

Publications often combine osteometrics with illustrations, as in Peters' (1986a) work on distinguishing the appendicular bones of cattle from those of the closely related African buffalo. Some differences can be conveyed reliably by measurements or ratios of measurements, while others are best conveyed in a visual representation of the bones in question. My own opinion is that, with the possible exception of features in very small animals, one should employ metrical distinctions to describe more precisely features first discernable by visual inspection.

Taphonomic history can affect frequencies of measurable bones in an archaeofauna. I have worked extensively with prehistoric assemblages from East African localities that osteological and other archaeological evidence indicates were pastoralist encampments (Gifford-Gonzalez 1998). Bones were broken to fit into cooking pots (Marshall 1990), possibly for bone grease manufacture, after their discard trampled by herds and flocks, and after burial sometimes split open by soil action. At one such site, (Gifford et al. 1980), identifiable specimens' modal maximum dimension was 3–6 cm (1.8–2.6 inches), and among about 600 carpal and tarsal specimens – usually among the most durable of elements – a student study found seven specimens, measurable with von den Driesch's system. Richard Meadow (personal communication, 2007) reports similar problems with prehistoric bovine samples from South Asian pastoralist settlements. Selective use of some elements for bone tool manufacture can also affect measureable specimens. British zooarchaeologist Sebastian Payne (personal communication, 1973) recounted his initial elation that simple measurements could reliably distinguish sheep from goat metacarpals (Payne 1969) and his subsequent disappointment upon realizing that metacarpals of both species had been popular materials for ancient bone tools, obliterating their measurable features. To deal with the fragmentary state of many archaeofaunal specimens, Meadows (1999) developed a method for comparing metrics from different skeletal elements, using logarithms of the measurements taken in relation to those from the same elements of a "standard animal" for the species. This Logarithmic Size Index (LSI) is widely used by zooarchaeologists in Eurasia monitoring body size changes in relation to domestication.

6.1.3 Osteological Guides to Wild and Domestic Animals

This listing here is not exhaustive but cites reference materials in North American zooarchaeology, with a few from Europe and Africa added. Some introductions to zooarchaeology, including Reitz and Wing's (2008) *Zooarchaeology*, contain good illustrations for the beginner. Classic sources include Lawrence's (1951) *Guide to postcranial characters of deer, pronghorn, and sheep-goat,* Schmid's *Atlas der Tierknochen/Atlas of animal bones* (1972), and Stanley Olsen's Peabody Museum publications (1960, 1972a, 1972b, 1968, 1973), which include mammal, bird, reptile, and amphibian reference drawings and photographs.

More recent publications with profuse photographic documentation and available in digital form, include France's (2009) *Human and nonhuman bone identification: A color atlas* and Adams and Crabtree's (2008) *Comparative skeletal anatomy: A photographic atlas for medical examiners, coroners, forensic anthropologists, and archaeologists* and (2012) *Comparative osteology: A laboratory and field guide of common North American animals.*

Additionally, textbooks of veterinary anatomy (Barone 1976; Sisson and Grossman 1975) provide valuable information on the relation of soft tissues to bone, as well as details of domestic animal osteology.

Other publications for North Americanists include B. Miles Gilbert's *Mammalian Osteology* (1990) and Brown and Gustafson's (1979) *Key to the postcranial skeletal remains of cattle/bison, elk and horse*. The latter is an excellent example of the multiple view approach to distinctive osteological features.

Classic articles with illustrations include those on distinguishing sheep from goat (Prummel and Frisch 1986; Boessneck 1969; Zeder and Lapham 2010; Zeder and Pilaar 2010), North American deer from sheep and goat (Hildebrand 1955), and different species of equid, with a focus on Africa (Klein and Cruz-Uribe 1996). Pacheco Torres et al. (1986) authored *The osteology of South American camelids*. Larger East African mammals are depicted in *A guide to post-cranial bones of East African animals: Mrs. Walker's bone book* (R. Walker 1985) and the Peters studies (1986; 1986a, 1986b; Peters and Brink 1992) mentioned earlier. Beisaw's (2013) *Identifying and interpreting animal bones: a manual* contributes a perspective on the process of analysis.

Veterinary and meat science literature has produced books of value to zooarchaeologists, among them, Sisson and Grossman's *Anatomy of domestic animals* (1975; Getty 1975). In addition to fine illustrations of bones of horse, cattle, pig, goat, dog, and chicken, it illustrates muscles, joints with ligaments, and other soft tissue features of interest to zooarchaeologists. In earlier editions – the book has been in print since before the internal combustion engine replaced horses – the illustrations are somewhat sharper. Another relevant veterinary anatomy book is *Muscles of the ox* (Butterfield and May 1966), with detailed descriptions and some illustrations of the origins and insertions of major muscles on elements of the appendicular skeleton, plus a short discussion of differences between cattle, buffalo, and bison. Recent English translations of König and Liebach's (2007) atlas, as well as Robert Barone's (1976) *Anatomie comparée des mammifères domestiques*, are other well-illustrated references that illustrate muscle origins and insertions on axial and appendicular elements.

Those working with rarer species should bear in mind that zoological research on vertebrates in the nineteenth and early twentieth centuries centered more on bones and morphology than in later years, with beautiful illustrative plates (e.g. Perrier 1893–1932). Vertebrate paleontological articles have dealt in detail with bones, and older works were often very well illustrated (e.g. Piveteau 1952–69; Pictet 1980 (1853–1857)). Zooarchaeological researchers should therefore consider searching this older literature for reference illustrations of the taxa with which they are working. Crania and mandibles of rodents are commonly illustrated in standard field guides to these taxa, even if skulls of larger animals are not.

6.2 Body Size Estimation

Zooarchaeologists may wish to estimate the size of the animal from which a skeletal element was derived for several reasons. These include diagnosing domestication, discerning the proportional representation of the sexes in a sample, monitoring environmental changes that affect achieved body size, inferring age in vertebrates of *indeterminate growth*, that is, those that continue growing over a long span of their lives, such as tortoises and some fishes, and by extension, assessing the intensity of human predation on them, and estimating the weights of prey animals acquired.

6.2.1 Diagnosing Domestication

For many years, size differences have been used to assign individual specimens to wild or domesticated forms of the same species. The assumption, based in part on comparing wild representatives of certain species with non-modern domestic breeds of the same taxon, is that domesticates are usually smaller. Zeder (2001) strongly cautioned against uncritically assuming that larger animals are wild and smaller ones domestic, especially when studying the earliest phases of domestication. Her metrical study of wild and domestic goats from Iran and Iraq demonstrated that a north-south cline in size exists in wild populations. This would be expected, according to Bergmann's Rule, which stipulates that members of a species living in higher latitudes will have larger body size than those farther south.

Zeder argues that zooarchaeologists have sometimes compared modern wild goats from the northern (and larger body size) end of their geographic range with archaeofaunal goat remains from the southern end, leading to inaccurate inferences about their domestic status. She contends that changes in (aggregate age-at-death) may be a more reliable indicator of early domestication. The same point regarding size as a poor diagnostic for domestication was made by Rossel et al. (2008) for early domesticated donkeys in Africa, and by Rowley-Conwy (1995) with regard to putative domestic cattle and pigs in different parts of Europe. In the case of pigs, ancient and modern DNA has added further complexity to using size to diagnose domestication. For many years, zooarchaeologists working in Europe assumed that the wide size range of pig molars and other elements observed in some Neolithic sites resulted from acquisition of the still abundant wild boar, combined with slaughter of domesticates. The range of sizes was thought to have been produced by combining two samples of sexually dimorphic pigs, large wild and smaller domesticates introduced from the Near East, into one culturally combined and deposited sample (Rowley-Conwy 1995). This may be the case in some European situations, but osteological and ancient DNA analysis revealed that some of the large, "wild" pigs in Neolithic sites displayed markers indicating domestication, including genes for the spotted coat color typical of domesticates and displayed haplogroups typical of later European domestic suids. In some earlier Neolithic sites, both domestic stocks of two different body sizes are represented in the mitochondrial DNA. The genetic evidence testifies to a relatively rapid process of replacement of domestic pigs introduced from Southwest Asia by newly domesticated swine derived from European wild boar (Larson et al. 2007).

6.2.2 Size Differences Over Time and the Historical Ecology of Human Prey Species

Size differences in a long-term chronological sample of one species may reflect both ecological factors and, in cases of domestication, human selectivity. Klein (1986, 1991) asserted that changes in sizes of South African carnivores and mole-rats during the Pleistocene reflected climatic change. Changes in the modal size of individuals of a species, especially the case with species of indeterminate growth, in a time series of archaeofaunas can also reflect changes in the intensities of human cropping on that species (Klein and Cruz-Uribe 1983; Stiner et al. 2000; Broughton 1997).

6.2.3 Bone Size as an Estimator of Body Size

Zooarchaeologists may wish to know the body size of an animal, quantified by body dimension (e.g. total length) or by weight, to estimate meat yields and thereby to assess handling costs and return rates or aspects of predation. Whatever their motivations for estimating the body size of vertebrates from archaeofaunal specimens, zooarchaeologists can turn to literature in theoretical evolutionary biology and applied wildlife management for guidance in developing formulae and, in some cases, for published information on a taxon.

Linear relations exist between the dimensions of certain skeletal elements and body size, especially length or height of the animal. Strong positive correlations between skeletal weight and total body weight exist, as well. Reitz and Wing (2008: 64–69) outline approaches to simple linear and allometric scaling. Even in circumstances in which size relations of skeletal elements to living body size are not known for a given species, zooarchaeologists can use established procedures for collecting samples, measuring bone, and fitting regressions that permit size estimation, either of body weight, skeletal weight, body length or, in the case of quadrupeds, height at shoulder (Chaplin 1971; Casteel 1976). Some authors have inserted a note of caution about taphonomic effects on ostensibly measurable elements, which would include both heat stress and, for elements of small prey, erosive effects of digestion (Tollit et al. 2004).

6.3 Sex Determination

Some traits of vertebrate skeletons vary with an individual's sex, as the result of one of several selective pressures. Physical competition for mates by one sex may produce size differences between the sexes. In species where male-male sparring for dominance allows winners greater access to reproducing females, as, for example, in deer and sea lions, males are larger than females due to an evolutionary "arms race" in body size. The same pressures may have selected for differentially developed body segments, as in larger neck muscles employed in clashes with other males. Specialized, sex-specific structures, such as the antlers or horns of many male artiodactyls, or canine teeth in pigs and primates, may evolve in this same selective context. Alternatively, certain physical traits may be selected for without such direct, same-sex competition, as when a potential mate of the opposite sex chooses to mate with an individual possessing an extreme expression of the trait. Such sexual selection directs development of secondary sexual characteristics in the sex being chosen, as in the case of the peacock's tail displayed to peahens.

Selective pressures other than competition for mates can also result in sexual dimorphism in size. Size differences between males and females may be the result of intraspecific niche partitioning, as Brown and Laziewski (1972) argued for the great sexual dimorphism in weasels. They contended that the much larger male weasels could not enter small burrows exploited by females living in overlapping foraging ranges, thereby guaranteeing the females access to prey without male interference. Erlinge (1979) proposed another explanation for weasel sexual dimorphism: female weasels rear their offspring without help from males, and their size better fits the energetic demands of foraging for a litter. Smith (1982) assesses explanations of the fact that, among raptorial birds that mate for life and share foraging ranges, females are larger than the males and dominant to them early in the breeding season. While niche-partitioning explanations have been proposed, Smith favors a behavioral explanation, in which female dominance dampens potentially lethal competition between the mates and ensures the female first choice at shared food, ultimately enhancing the reproductive success of both sexes.

Finally, the divergent demands of reproduction on females and males can produce physical differences between the sexes. Among the most common of these in placental mammals is differences in pelvic structures, related to accommodating birth of well-developed young. This contrast is well known in physical anthropology, and it holds for many other mammals as well. Measurable differences in the proportions of innominates, sacra, or femora may also distinguish female from male elements in an assemblage because these elements are associated in the pelvic girdle and articulating leg bones. Recent studies have shown that male and female primates display body-segment and bone-density differences that reflect the divergent selective pressures operating on females during pregnancy and while carrying their young, despite their living in the same groups and engaging in overall similar modes of locomotion as males (Morbeck et al. 1997).

In this connection, Greenfield (2006) noted a metrically distinguishable difference in the height of the acetabulum (hip socket) rim in male versus female bovid innominate bones, which clearly stems from the functional differences in the pelvic structure in the sexes. Among birds, only females deposit bone in their medullary cavities as a prelude to producing eggs. Driver (1982) noted this trait as a possible means of diagnosing site seasonality with wild bird species; van Neer and Lentacker (1996) used medullary bone to diagnose the season of slaughter in Roman-period Egyptian domestic fowl. Presence of sex-specific anatomical features such as antlers in deer or canine teeth in horses may also be used to diagnose sex.

Whatever their ultimate causes, zooarchaeologists can use sex differences in osteology to infer the probable sex of individual archaeofaunal specimens. If a single archaeofaunal species sample displays a generally bimodal distribution in skeletal element size, zooarchaeologists have inferred sexual dimorphism in the sample. Given a sample of sufficient numbers of specimens, it may be possible to explore whether sex-specific predation (e.g. Lyman 2007) or management of domesticates existed.

Higham and Message (1969) were among the first to use osteometrics to discern prehistoric cattle herd composition by sex. While size–based sexual dimorphism is the case in many wild species, domestic taxa can present exceptions to the bimodal rule. In meat- and wool-oriented production systems, male cattle, sheep, and goats are kept alive past sexual maturity for their economic value. However, they are usually castrated before or as they reach full growth, because castrated males are more manageable when herded with females and young and more tractable with humans. Castrates grow differently from either females or intact males, building body mass more swiftly and developing longer limbs than bulls (Rogol 1996; Martin et al. 1979). Explaining greater growth in castrated males was once considered straightforward, as androgens (male sex hormones) were assumed to damp down on Growth Hormone, and in the absence of testes, androgen production would be slower and lower. However, more recent research shows that androgens enhance and stimulate growth hormone in males, and that estrogens, found in both females and males, are more directly linked to epiphyseal fusions at the end of growth in humans (1969).

A recent, innovative project by Swedish zooarchaeologists and geneticists used a single-nucleotide polymorphism (SNP) that indicates sex in DNA recovered from archaeological metacarpals and metatarsals of cattle to assess the accuracy of measurements zooarchaeologists had used earlier to assign the specimens to male and female sexes (Watson 1969). They found that, overall, the key measurements employed did quite well in distinguishing males from females, and that measurements of males appear to be able to discriminate between bulls and castrated males, which cannot be differentiated from their DNA (Teldahl et al. 2012).

Davis's (2000) study of skeletons from one flock of Shetland sheep presents actualistic data on maturation of ewes, rams, and wethers (castrated males), including tooth eruption, epiphyseal fusions, and achieved size. Wethers were found to have longer, more slender long bones than rams due to a longer period of growth before epiphyseal fusion (see also *Endochondral Bone Fusion*, below). Davis cautioned that only osteometric differences in pubis shaft thickness, long bone lengths, and long bone shaft widths reliably distinguished ewes, rams, and wethers.

6.4 Estimating Age at Death from Osteological Markers

Zooarchaeologists have for some time studied the aggregate pattern of ages at death of archaeofaunal mammals, with the goal of linking such patterns to human predation practices or herd management systems. Studies of domestic fauna have often been referred to as "kill-off patterns"(Payne 1973), while studies of human predation have referred to "mortality patterns," following terminology developed in demographic studies of living animal populations. Despite terminological differences, these approaches are the same. Each attempts to discern the effects of humans (or pre-modern hominins) on animal populations through studying the ages at death of animals recovered from an archaeological sample.

Those working with domestic animals have argued that age- and sex-specific slaughtering patterns, and hence goals of ancient animal exploitation, can be reconstructed from aggregate ages at death (Payne 1973). Documented dairy cattle herds are numerically dominated by cows and heifers and male young-of-the-year, with rare bulls or steers (castrated males). Beef herds generally have a more balanced sex ratio, but nearly all males are steers rather than bulls. Wool-producing sheep flocks are also more or less sex-balanced, but again, most males are castrated. In all cases, human intervention in the demographics of the species produces the pattern of survivorship (Payne 1973; Redding 1981). Davis (1987) argued that the shift from food-oriented sheep exploitation to that focused on secondary products such as milk or wool could be traced by examining modal ages of the dead domestic stock in sites. Problems and potentials of this approach will be explored further in Chap. 22. New, independent lines of evidence from pottery residue analysis can help contextualize purely zooarchaeological indicators of dairying (Chap. 23 (Chaplin 1971; Ruscillo 2006; Silver 1963)).

Studies of age-sex composition in archaeofaunal samples rely on two distinct areas of research and analysis:

1. Accurately determining the sex and age at death of specimens;
2. Assigning a meaning to the aggregate mortality pattern of archaeofaunal specimens.

This section examines aging methods, and Chap. 22 will consider mortality pattern analysis in more detail. No single, uniform method of determining age at death exists today. Several different methods, most developed in wildlife biology or physical anthropology, are currently being used to estimate age-at-death. Most have been checked against known-age samples of mammals and have benefited from methods and perspectives drawn from wildlife biology and ecology. However, O'Connor (2006) has stressed that much more actualistic research is needed to reduce ambiguities in the present reference data.

O'Connor (2006) also noted a rarely acknowledged problem in age estimation research: deciding the appropriate level of precision in one's age estimates in relation to the intrinsic variability in the features used to estimate age in animal populations. Examples of this are discussed in more detail below, as various ageing methods applied to mammals are reviewed.

6.5 Osteological Estimations of Age

Bones, as opposed to teeth, remodel throughout life, and they also go through a series of developmental phases. In some mammal species, these phases and their timing have been relatively well studied and can be used to estimate the age at death of a maturing animal.

6.5.1 Cranial Suture Fusion

The cranium is composed of numerous dermal bones, joined together by a special type of joint called *squamous sutures*. In mammals, these joints fuse over an individual's development, some so thoroughly that they are difficult to see in mature individuals (Fig. 6.2). Cranial sutures fuse during adulthood in humans, and as with epiphyses, have a long history of use in ageing human remains. Fusion ages for

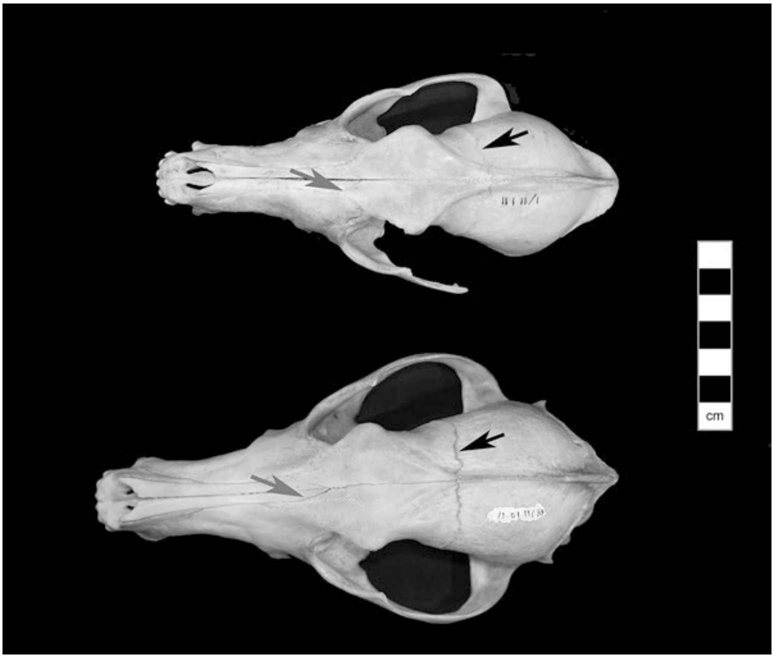

Fig. 6.2 Two adult coyote (*Canis latrans*) crania, showing an older adult (upper) and younger adult (lower). Note more fused nasal-frontal (gray arrows) and frontal-parietal (black arrows) regions in older individual. Larger (lower) individual was a road kill from the Rocky Mountain area, and the smaller (upper) was a depredation kill from the Santa Cruz Mountains (Photo by author of specimens from Anthropology Teaching Laboratories)

cranial sutures are known for domestic animals. They are much less well understood for most wild mammal species, largely because biologists have relied either upon tagging records of birth dates in managed wildlife areas or upon more easily observable dental eruption and wear, or they have made thin sections of dentine from incisors readily extracted from the jaws of dead mammals (Davis 1987:158–160).

In well-studied taxa such as humans, ages of specific cranial suture fusions vary from one individual to another, providing a range of ages rather than a precise number. Although much work is needed to use this trait in zooarchaeology, and some indicators suggest that it may not be so useful in some taxa as it is in humans (Robinette et al. 1957; Mitchell and Smith 1991), human skeletal biology nonetheless offers models for analyzing and quantifying these fusions.

6.5.2 Endochondral Bone Fusion

In mammals, epiphyses fuse to their adjacent diaphyses at more or less predictable times over the span of an animal's maturation (Fig. 6.3). Bones with unfused or fusing epiphyses can therefore be used to estimate age-at-death, a method employed for over a century with human remains. However, a good deal of individual variation exists in the calendrical age at which a specific epiphysis fuses, and fusion ages should be considered an age estimate rather than a precise determination.

Zooarchaeologists and biological anthropologists use these developmental features as indicators of age-at-death, at least into early adulthood. Ages of epiphyseal fusion are reasonably well known for domestic animals (see Chaplin 1971; Ruscillo 2006; Silver 1963 and references within; Wilson et al. 1982). However, they are poorly documented for many wild species for the same reasons that wildlife biologists have not extensively studied cranial suture fusions.

Some archaeologists have compared the age estimates based upon epiphyseal fusions against those derived from dental eruption and wear (Chap. 7). Zeder (1991) combined these approaches in ageing domestic sheep and goat samples from several sites in the Kur River Basin, Iran.

Zooarchaeologists, who deal mainly with isolated postcranial bones, are often more highly motivated than zoologists to document epiphyseal fusions and have contributed several major epiphyseal fusion studies of wild mammal species. Purdue (1983) linked age-at-death records for managed white-tailed deer, *Odocoileus virginianus*, to epiphyseal fusions, supplementing an earlier study by zoologists Lewall and Cowan (1963) on black-tailed (mule) deer, *Odocoileus hemionus*. Carden and Hayden's (2015) epiphyseal fusion study for European fallow deer *Dama dama* is another such example, as are Walker's (1987) study of Rocky Mountain bighorn sheep *Ovis canadensis* and Weinstock's (2009) study of brown bear *Ursus arctos* epiphyseal fusion.

It is often possible for zooarchaeologists to develop fusion tables using museum specimens. Storå (2001) used museum collections of modern ringed seal *Phoca groenlandica* and harp seal *Phoca hispida* for which environmental monitors had

Fig. 6.3 Tibia and fibula of a female northern fur seal (*Callorhinus ursinus*), showing recently fused proximal and fusing distal epiphyses with metaphyseal lines still clear (Photo by author of specimen from California Academy of Sciences)

estimated ages by dental cementum annulus analysis (see below). Storå correlated dental annuli-based ages (Chap. 7) with osteometrics and epiphyseal fusions in the associated skeletons. This strategy could be used on almost any species for which complete skeletons exist. Moreover, since many wildlife managers use sectioning of incisor cementum, it may be possible either to use existing data on the age of a specimen derived from this method or to make a case for such a time-honored study to collections managers.

Another actualistic approach to epiphyseal fusion involves studying natural mass deaths or mass wildlife culls. Haynes studied modern African elephant behavior and population dynamics as a modern analogue for late Pleistocene Eurasian and North American mammoth and mastodon ecology and for human predation on them. Most of his research was in Hwange National Park, western Zimbabwe (Weinstock 2009), where the overall numbers of elephants in the park rose above sustainable levels. Hwange Park officials shot entire elephant family groups and had the carcasses butchered for meat distribution to local people. Haynes was able to correlate long bone epiphyseal fusions with existing ages from dental development or from Park records. Such examples show that zooarchaeologists can exploit other situations to develop fusion tables without having to collect their own specimens.

6.5.3 Bone Durability and Missing Age Classes

Younger animals' bones do not resist destructive processes so well as do those of older animals of the same species, and archaeofaunal samples are thus highly likely to be biased against remains of younger age classes. This phenomenon has been known in human paleodemography for some time (Haynes 1987, 1991) and was recently shown to affect survival of children's bones on an historic scale. When burials in a California cemetery for which good burial records existed had to be relocated, physical anthropologists found that children's remains were substantially under-represented (Acsádi and Nemeskéri 1970; Buikstra 1981). They also found that skeletons of older people, whose bones were likely calcium-depleted at the time of death, were represented in lower frequencies than predicted by burial records. Parallel taphonomic problems have been documented for dentally based ageing approaches, as will be discussed below.

Paleodemographers have attempted to correct for preservation biases in human skeletal samples by interpolating a certain proportion of infants and members of very young age classes based on certain theoretical models of population structure (Walker et al. 1988). For zooarchaeologists, this problem of missing age classes is more vexing because we know that animals taken by humans seldom randomly sample the animal population from which they are drawn. Rather, we assume that they are a sample produced through age-specific choices of human predators or animal keepers. It is therefore not logically defensible for us to assume a given proportion of very young animals existed in our samples, because of the possibility that they may have been specifically excluded in human patterns of predation or management. This topic will be taken up again in Chap. 22 with regard to mortality profiles.

6.5.4 Osteohistological Age Indicators

As seen in Chap. 4, the nature, density, and architecture of bone cells and noncellular material change over the lifespan of a vertebrate. Dammers (2006) monitored changes during growth and development, which had prior applications in human skeletal biology, forensics, and paleontology, and its potential for application in zooarchaeology. Among the findings she reports are that secondary osteons and osteon fragments (by-products of remodeling) increase with age and that castration reduces bone tissue density in experimental animals (Dammers 2006:27–28). The latter could provide an independent check on the validity of the definition of castrates in an archaeofaunal sample by osteometrics.

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Chapter 7
Bone's Intrinsic Traits: Age Estimation from Mammalian Dentition

Dental morphology is closely tied to species' feeding adaptation, and the general features of tooth growth and development are well understood. Because teeth are more durable than bones, they tend to preserve well in identifiable form. For all these reasons, they have more commonly been used to identify species and to estimate age-specific deaths in archaeofaunal samples. This chapter first outlines ageing methods based on dental growth and development features: cementum annuli, eruption schedules, and radiological analysis of tooth development. It then describes ageing methods based upon the attrition, or wearing away, of the dental enamel crowns: comprising wear-stage analysis and remnant height of the enamel tooth crown. The next section considers taphonomic effects on dentitions of young animals, showing that, though postmortem processes may affect dentitions less than they do bones, the loss of younger age classes should not be discounted when studying teeth. The following section discusses ageing methods in terms of precision and accuracy, making the point that some types of research questions can be pursued with age estimates that are of lower resolution but very accurate. The chapter concludes by discussing the challenges presented by the variation intrinsic to natural systems, including patterns of growth and development, to formulating appropriate statistical approaches to age estimation.

7.1 Age Estimates Using Growth Structures: Tooth Eruption and Wear

Some animal species give birth through much of the year, but others have birth seasons restricted to only a few weeks, permitting very precise estimation of age and season of death. Among hoofed animals, North American bison and African wildebeest are extreme examples, each species calving within less than a month. All members of one yearly birth cohort thus begin erupting and wearing their teeth over

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the same time span. Even taking into account individual variability in tooth eruption age, in such a species, a cohort of young-of-the-year is readily distinguishable from the previous and subsequent ones one by their patterns of dental eruption and wear. While dental eruption and wear are continuous, such a tightly constrained birth season marks the "starting line" of each year's cohort.

Over the last 40 years, zooarchaeologists studying bison hunting in North America have used tooth eruption and wear patterns combined with other evidence to reconstruct the modal ages of the young-of-the-year in their sites and, from that, their approximate seasons of death. At the Casper Site, a bison kill on the Wyoming High Plains, teeth of individual animals could be placed into clear-cut eruption and wear sets without intergrades (Frison 1974). This indicates that the Casper bison were hunted over a short time span, perhaps only a day, and other archaeological evidence also suggests that the site represents a very short-term occupation. Researchers in Europe and Southwestern Asia have for decades used tooth eruption and wear to create general age classes in domestic animals, as will be discussed later in this chapter.

What conditions this variation in tooth growth and eruption? Davis's (2000) study of castrated Shetland sheep found that, whereas such wethers showed delay in epiphyseal fusion of some long bones, the timing of their tooth eruption did not differ from that of intact males and females, and the sexes did not diverge significantly in their eruption schedules. Dental development thus does not appear to be so closely tied to circulating hormones as endochondral ossification.

Age estimates based on tooth eruption should be made with an understanding of the variability inherent in animal populations. Domestic animal studies have shown that even closely related individuals may diverge in ages at which a given tooth erupts. In several years' sampling of a herd of Boran breed cattle sired by very few bulls over the study period, at a Kenyan agricultural research station, determined that the average age of first permanent incisor eruption for cows was 108 ± 9.9 weeks, for second incisor, 137 ± 12.9 weeks, for third incisor, 165.7 ± 15.8 weeks, in a more or less normal distribution, with steers and bulls showing slightly different ages of eruption but similar patterns of occurrence (Carles and Meidie Lampkin 1977). Their study found no evidence for the influence of maternal health on the 20–32 week variation in eruption times. The same authors (Carles and Meidie Lampkin 1977) further explored the growth correlates of "early erupters," animals with first incisors erupting earlier than the mean age of eruption, vs. that of "late erupters," those with first incisors erupting later than the mean age of eruption, among 191 steers from this same population. They found that early erupters were statistically significantly heavier than were late erupters ($p < 0.01$) for the first 3.75 years of life, that is, into their achieved adult size. Thus, it appears that, even among closely related animals, a genetic basis exists favoring some polymorphism in the population. Such a pattern makes sense in terms of the stresses to which traditional African cattle had to adapt, with starvation selecting against animals of greater size during cyclical droughts, but greater success in male-male competition or herder selection of larger calves, rewarding larger males in times of good forage. A parallel case of sustained conservation of a simple balanced polymorphism for male horn size, has been iden-

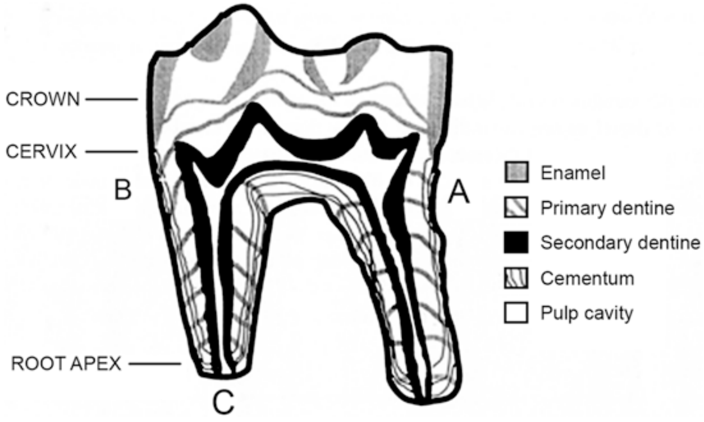

Fig. 7.1 Longitudinal section of a ruminant molar, showing the location of dental tissues. Letter A indicates the distal side and B the mesial side of the tooth, and C the root apex with acellular cementum, the top of the arch between the roots holds the root pad, which is another area of acellular cementum. Annular rings develop in the cementum (From Pike-Tay (1995:275, Fig. 1), used with permission of the author from the Open Access journal *Archaeofauna*)

tified among feral Soay sheep of St. Kilda Island (Johnston et al. 2013), as will be discussed later in this chapter. Because of such factors, and as with epiphyseal fusions, age-at-eruption statistics for ruminant species should be taken as statistical estimates of calendrical age, rather than very precise age data.

Even taking such variation into account, age estimation by tooth eruption schedules can only take the zooarchaeologist so far. Many mammals live for years after their permanent teeth erupt, and eruption-based age estimates cannot define these individuals' ages. The next section reviews incremental growth structures to determine age-at-death. A later section outlines ageing methods based on dental attrition or wear.

7.2 Age Estimates Using Growth Structures: Dental Cementum Annuli

Rather precise estimations of age-at-death of adult and immature mammals can be obtained by counting annular growth rings in the dentine of tooth roots or in the "pads" of non-cellular bony cementum at the base of molars (Fig. 7.1). This method was first developed in wildlife managers, who focused on the dentine roots of incisors, which are readily extracted from jaws of dead animals in the field (Klevezal and Kleinenberg 1969; Laws 1952; Sergeant and Pimlott 1959; Simpson and Elder 1969). As with tree rings, these features grow annually in sets of two rings, one reflecting a slower-growth phase and the other swifter growth. These paired cementum annuli (Latin singular, *annulus*) are then counted to reckon the number of years an animal lived and can be used to assess the growth phase during which it died.

Fig. 7.2 Cross-section micrograph of a bighorn sheep molar, showing cementum annuli, with innermost (earliest) at the left and the outermost in formation at the time of death on the right (Unpublished micrograph by Christopher O'Brien, used with permission of C. O'Brien)

The process of deposition of darker and lighter bands in cementum, and the role of environmental and physiological factors in structuring them, are still under investigation. Through experimentation, Lieberman (1993) concluded that darker bands are more mineralized than the lighter bands and that this is due to a slowing in the production and deposition of collagen, as the rate of mineralization of collagen stays constant (Fig. 7.2). Klevezal and Kleinenberg (1969) originally argued that cementum annuli recorded seasonally variable environmental conditions, and Lieberman (1993) noted that dark banding in modern specimens is associated with seasons when food is restricted. Later research in biological anthropology and mammalogy has highlighted the subtleties of these "records" of physiological stress. Klevezal (1996) summarizes evidence that particularly strong banding can reflect pregnancies. While it has been generally assumed that the annuli reflect seasonal variations in diet or environment, a close study of relatively well-provisioned humans (Wittwer-Backofen et al. 2004) suggest that annular growth bands are deposited even in mammals experiencing little seasonal stress.

Lieberman (1994) proposed two mechanisms for development of this banding. First, Sharpey's collagen fibers would take on a more vertical orientation when subjected to higher mechanical stress, such as chewing harder foods during the lean season than an animal would undergo masticating softer foods. Second, the lower nutritional content of the food may itself slow deposition of tissue. Cool et al. (2002) further investigated the role of collagen fibers versus hydroxyapatite in producing the perceived banding in cementum. They found that mineral crystals were responsible for the seasonal banding, and that Sharpey's fibers, although showing a radial organization in the cementum, did not themselves produce the banding.

Actualistic checks of one mass death of North American pronghorns with a known season of death (Lubinski and O'Brien 2001) and of humans of known age-at-death (Wittwer-Backofen et al. 2004) have shown this to be a very accurate ageing method. It has been applied to a variety of archaeological cases (Pike-Tay 1991; Savelle and Beattie 1983; Koike and Ohtaishi 1985; Coy and Garshelis 1992; Clarke et al. 1992; Coy et al. 1982).

The cementum annulus method has drawbacks; it is destructive, requiring that a tooth be sectioned and a thin section prepared for examination under transmitted light, polarizing light, and/or scanning electron microscopes. Museum curators are usually reluctant to permit such testing as long as other, non-destructive methods are available. The trade-offs between a precise but destructive estimator of age-at-death and other, less precise methods that are nonetheless accurate will be taken up in the last part of this chapter.

The skills required for preparing and consistently counting cementum layer bands require time to develop and are best assimilated in apprenticeship with an experienced researcher. Lieberman (1994) and Pike-Tay (1995) discuss details of preparing teeth for analysis. The sampling regions on tooth roots have varied with researcher, with some using the sides of the roots and others the cementum "pad" between the roots of the tooth. Pike-Tay (1995) argues that the pad area preserves cementum layers more reliably (see also Balasse 2003). Although annular bands are countable, the potential for inter-observer divergence in counting exists. Two developments have improved annulus counting. First, Rissman (1987) applied a now widely used, open-access method for computer-enhancing images of annuli, which produces more standardized and accurate reckoning. Second, Wall-Scheffler and Foley (2008) presented a fully digitally based approach to "reading" the banding: digital cementum luminance analysis (DCLA), in which the relative levels of luminance under polarizing of different annular bands are scored from photographs by a computer-assisted program. They used a known-age-at-death sample of Soay sheep teeth to assess whether DCLA acceptably estimated age-at-death, which it did to a high level: $R^2 = 0.890$, $P < 0.001$ (2008:18).

Stutz (2002) cautioned that diagenetic alteration of cementum can develop banding that may mimic physiologically deposited structures. He does, however, suggest a method for distinguishing these two types of structure.

At a much finer grain of analysis, researchers have discovered that it is possible to distinguish via SEM the daily cycles of enamel growth during the formation of a tooth (Dammers 2006). This painstaking work can result in a very precise estimate of the age-at-death of younger individuals. However, it is more relevant to researchers interested in details of individual growth and development, such as paleoanthropologists, than to zooarchaeologists.

7.3 Age Estimates Using Growth Structures: Dental Root Development

Carter (2006) presented a radiographic approach to documenting the development of teeth in two European cervid species, red deer (*Cervus elaphus*) and roe deer (*Capreolus capreolus*). To document tooth development, Carter defined ten descriptive stages for permanent tooth development, plus four for deciduous teeth (Table 7.1), from the

Table 7.1 Outline of tooth development scoring system used by Carter (2006:46, Figure 7)

Stage and Score		Description
Deciduous	**Permanent**	
(7)		Half root length formed
(8)		Late root formation
(9)		Full root length (apex open)
(10)		Full root length (apex closed)
	1	Evidence of a crypt
	2	Evidence of mineralization
	3	All cusps mineralizing
	4	Infundibulum formation
	5	Crown formation complete
	6	Early root formation
	7	Half root length formed
	8	Late root formation
	9	Full root length (apex open)
	10	Full root length (apex closed)

formation of crypts in which tooth crowns develop to full development of the roots. Carter discerned hitherto undocumented but consistent developmental patterns of red deer dental roots. He argues that certain root development patterns occur over a short developmental span, and that even isolated teeth, if their roots are preserved, can be used to estimate age-at-death.

Carter's technique has the advantage of being non-destructive and equally applicable to modern and archaeological specimens. It does require access to portable or fixed radiographic equipment for x-raying teeth still in maxillae or mandibles. Its main limitation is that described earlier for eruption: limitation to the maximum span of tooth development, 3–4 years of age in the case of larger deer.

Checks with known age-at-death samples from both species showed that Carter's method provided accurate estimates to the age when all permanent teeth had fully developed roots. Given that deer give birth seasonally, Carter (2006) used this technique to evaluate proposed seasons of site occupation, degrees of sedentism or of logistical foraging in Early and Middle Mesolithic sites in northwestern Europe. A taphonomic note should be inserted here for zooarchaeologists considering this method: archaeofaunal teeth often display damaged or absent roots, either because of pre-recovery processes or poor post-recovery handling. Researchers contemplating applying this method should check beforehand on the preservation of roots in any collections they wish to analyze.

7.4 Dental Attrition-Based Age Estimation Methods: Scoring Occlusal Wear Patterns

Most prey animals in Pliocene to historic archaeological sites are hoofed animals, or *ungulates*. Two- or four-toed ungulates of the order Artiodactyla include deer, antelopes, cattle, sheep, goats, pigs, camels, and giraffes. Members of the order

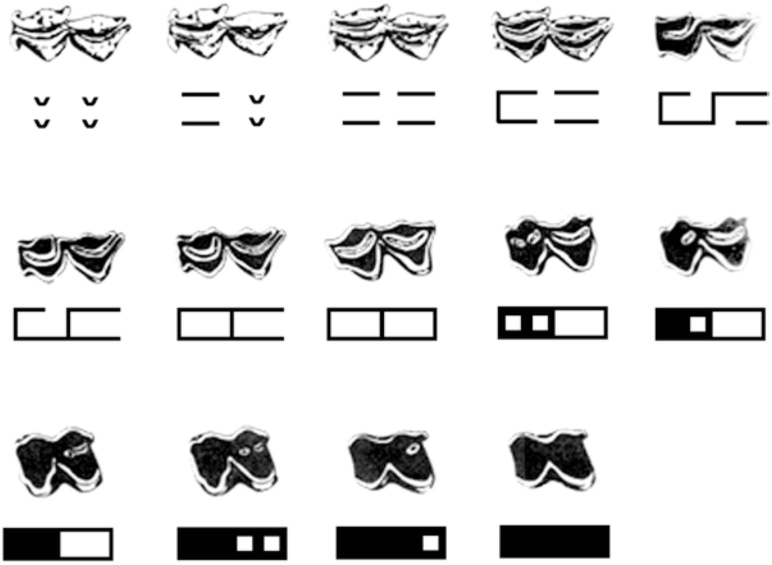

Fig. 7.3 Payne's occlusal wear stages for first and second lower molars of domestic goat, wear stage above and shorthand notation below (From Deniz and Payne 1982:162, Fig. 4), used with permission of authors and BAR Publishing)

Perissodactyla such as horses, donkeys, tapirs, and rhinoceroses have one or three toes. All these mammals eat leafy vegetation, either exclusively or in combination with other plant foods. Plant leaves are high in silicon content, and ungulate premolars and molars quickly wear away cusps of their enamel teeth. This exposes the dentine underneath and produces an irregular, grater-like surface of enamel ridges and softer dentine valleys that wear at different rates. This occlusal (chewing) surface of teeth macerates leafy food.

Tooth crowns continue to wear over an herbivore's life, due to the abrasives in plant tissues and grit on the vegetation. Species adapted to rougher diets, especially grazers like horses and cattle, have very high enamel premolar and molar crowns. Wear to the crown exposes irregularities in patterns of enamel and dentine on the occlusal surface, much like a machine cross-section. In any given species and type of tooth, such enamel and dentine patterns change predictably from one to another in succession.

Zoologists began using this phenomenon as an ageing technique (Caughley 1965) by defining a succession of enamel-dentine patterns that emerge with wear in all individuals of a given species. Despite a lack of reference materials with known ages, researchers initially assumed that each "wear stage" that developed after eruption of the last adult tooth lasted for roughly equal durations in the use-life of a tooth (Spinage 1967, 1971).

British researchers working with late prehistoric and historic livestock have used occlusal wear stages to group and rank order ages-at-death. The most widely used systems are those published for sheep and goats by Sebastian Payne (Deniz and Payne 1982; Payne 1973, 1987), shown in Fig. 7.3, and by Annie Grant (1982) for cattle and pigs as well as caprines. Bouchud (1966) had earlier developed a scale for molar wear in reindeer/caribou. As noted earlier, North American archaeologists studying bison kill-butchery sites used combined eruption and wear stages to age individual dentitions (Frison and Todd 1987; Frison 1974; Frison and Reher 1970). Occlusal wear stages for other mammals have been defined more recently, including for proboscideans and rhinoceratids (Louguet 2006) and European wild boar (Magnell 2006), the latter based on known-age specimens.

The occlusal wear stage method has several acknowledged problems. First, occlusal wear stages are liable to inter-observer divergences in attributing wear stage (Levitan 1982). Second, given that wear stages are ordinal scale variables, it is difficult to compare and assess the results statistically, although mortality profiles constructed with stage data could be compared statistically (Chap. 22). Third, earlier applications of the method tacitly assumed that each adult wear stage represented time spans of roughly similar lengths. Fourth, until recently, no age values could be assigned to these stages, since there had been no studies of dentitions of known age-at-death animals. Finally, given the possibility that a given tooth could wear irregularly, it was always deemed best to age rows of multiple teeth, rather than the isolated teeth often found in many archaeological samples.

Actualistic research on the occlusal wear stage method has clarified some of these problems. Deniz and Payne (1982) undertook a longitudinal study of molar wear in three flocks of Angora goats on Turkish agricultural research stations, where records of each animal's age were available. After some awkwardness, they developed a technique for prying open a goat's mouth, cleaning its teeth, and scoring occlusal wear stages, returning repeatedly to assess wear in the same individuals. They were then able to determine how much calendrical time each stage lasted and how much inter-flock variation in molar wear patterns and rates existed. It emerged that certain stages, such as the central one in the first row of Fig. 7.3, lasted substantially longer than others, while some, such as the final wear stages shown, were very brief.

Deniz and Payne found that age estimates from occlusal wear stages within a single flock were within one standard deviation of the averaged actual ages of the animals studied. However, they found that different flocks varied significantly in their rates of tooth wear, with those on coarser forage wearing their teeth more swiftly. This has implications for absolute age estimates for archaeofaunal animals that consumed forage of unknown quality.

Jones (2006) undertook another, larger-scale actualistic study of dental wear in various "unimproved" and "improved" breeds of sheep in England and Scotland, using the Payne system. After repeatedly viewing and recording wear stages in known-age animals aged from a few to 84 months, Jones came to generally similar conclusions as Deniz and Payne regarding the sequence and duration of certain wear stages. Her report includes extremely detailed primary data relevant to anyone interested in ageing caprines or to undertaking parallel actualistic research in other breeds. In nearly all the sheep breeds Jones monitored, concordance exists in rates of eruption and wear, with the exception of later average eruption times in Soay sheep, which have been feral for centuries.

Jones found that Payne's stage H (her stage 9), at the center of the middle row in Fig. 7.3, can develop in the mandibular M1 by the end of the first year and last up to the seventh year. This illustrates Jones's point that wear stages on individual teeth are much less informative than the totality of all wear stages represented in a tooth row. The same wear stage develops later and lasts for a shorter time in M2 and, unlike in M1 and M2, it is normally the *final* wear stage developed in M3 (Jones 2006:161–163). Jones' (2006:165) tabulation of wear stages against actual ages revealed the variability inherent in enamel crown wear, while nonetheless showing central tendencies. The "problem" of variability will be addressed at the end of this chapter.

Greenfield and Arnold (2008) used dentitions from known-age-at-death sheep and goats in Manitoba, Canada to compare Payne's and Grant's systems for estimating age from tooth wear. Their analysis showed a strong correlation between the known age and estimated age based on tooth eruption and wear, which they argued is consistently accurate for animals over 6 months of age. Greenfield and Arnold found that Payne's system, including revisions based on the Deniz and Payne study noted above, produced less precise age-at-death estimates and hence mortality profiles, mainly due to Grant's finer subdivision of wear stages for younger animals. They recommended Grant's system be used for ageing and constructing mortality profiles, while noting that intrinsic inter-individual variability in earliest eruption and wear patterns will always be a confounding factor (Greenfield and Arnold 2008:848).

Other dental occlusal wear stage studies deserve mention. Zeder (2006) correlated epiphyseal fusions with Payne's occlusal wear stages in samples of wild sheep (*Ovis vigni* and *O. orientalis*) and goats (*Capra aegagrus*) housed at the Field Museum of Natural History, Chicago. Although no ages-at-death are known for these animals, this correlative comparison provides baseline data for wild forms close to the Southwest Asian domestic caprines. Zeder's study might convince curators of the value of allowing expert sectioning of a sub-sample for annular growth features in dental cementum, which would provide reasonable ages-at-death. Zeder's discussion of age estimates drawn from both ageing systems is instructive, showing general agreement in 82% for sheep and 88% for goats, if one admits estimates overlapping at the limits of their range. This range is probably conditioned by the species' underlying biological variability, plus, perhaps, regional populational differences within the sample.

Magnell (2006) studied tooth eruption and wear in European wild boar of known ages, using Grant's (1982) system for describing mandibular molar wear in domestic pigs. Asymmetries between left and right molar wear were noted, with 27% of individuals having a difference of one wear stage between left and right sides. Variance was displayed between the predicted age of eruption and actual calendrical age, which increased with the age of the animals, although the correlation by linear regression was still quite strong ($r = 0.971$, $p = <.0001$, $N = 57$, Magnell 2006:191). Finally, interpopulational differences were seen in the degree of correlation between calendrical age and tooth wear stage, with some displaying a stronger correlation than others. That is, some populations showed a very great range of individual variability in tooth wear, whereas others did not. Significantly, the range of variation increases with age, especially in animals older than 36 months.

7.5 Dental Attrition-Based Age Estimation Methods: Crown Height Methods

Another approach to age estimation using dental wear measures the height of the remnant enamel crown. Wildlife biologists used the crown height method for some time in the 1950s through 1970s (Lowe et al. 1980; Lowe 1957; Severinghaus 1949; Spinage 1971, 1972). Ducos first applied it to archaeological specimens in 1968. The most widely used technique over the last decades has been that developed by Klein and his co-workers (Klein et al. 1981, 1983), especially Cruz-Uribe (e.g. Klein and Cruz-Uribe 1984). Klein developed the method independently, from a theoretical equation advanced by Spinage (1971), to describe a variable rate of dental attrition.

Klein et al. used a known age-at-death sample of wapiti, the North American subspecies of the red deer (*Cervus elaphus canadensis*) to assess the efficacy of linear and curvilinear regression analyses in estimating age-at-death from remnant crown height measurements. Although a linear equation produced generally accurate estimates, given Klein et al.'s criterion that estimates fall within 10% of lifespan, they concluded that a curvilinear, quadratic equation for tooth wear produced the best age-at-death estimates (Klein et al. 1983: 11–13). Klein et al. constructed their quadratic equation from wildlife biologist Spinage's (1973) proposal that dental wear proceeds at a negative exponential rate, being swift early in life and slowing to an essentially constant rate in later life. Levine's (1979, 1982) findings on equid tooth wear using known-age ponies in New Forest, England, generally supported this principle, acting as a kind of independent test of Spinage's assertion.

The quadratic crown height method (QCHM) aims to estimate an age-at-death for a given measured tooth by taking into account this variable rate of wear. The parabola described by this equation is shown in Fig. 7.4. Application of the method

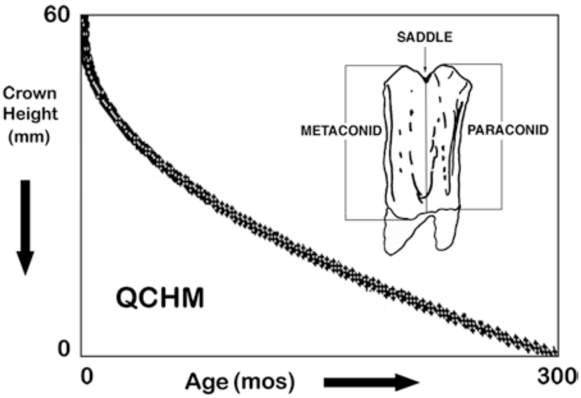

Fig. 7.4 The curve described by the quadratic crown height method (QCHM) of age estimation for a species with potential ecological longevity of 300 months and an average crown height at eruption of 60 mm, showing the hypothesized rapid wear initially and then a leveling of the curve with the lessening of the attrition rate. Ruminant molar illustrates three measuring points often used in prior crown height research (Figure by author)

assumes that, at least for ungulates, the same equation could produce generally accurate estimates of age-at-death for any species.

The QCHM terms for permanent teeth are as follows:

$$\mathrm{AGE} = \mathrm{AGE}_{\mathrm{pel}} - 2\left(\mathrm{AGE}_{\mathrm{pel}} - \mathrm{AGE}_{\mathrm{e}}\right)\left(\mathrm{CH}/\mathrm{CH}_0\right) + \left(\mathrm{AGE}_{\mathrm{pel}} - \mathrm{AGE}_{\mathrm{e}}\right)\left(\mathrm{CH}^2/\mathrm{CH}_0{}^2\right)$$

Where:

$\mathrm{AGE}_{\mathrm{pel}}$ is the "potential ecological longevity" (maximum lifespan) of the species;

$\mathrm{AGE}_{\mathrm{e}}$ is age at eruption of a specific tooth;

CH is the actual measured height of the enamel crown of the tooth, and

CH_0 is the height of the crown at eruption (when unworn), as determined from unworn specimens in an archaeofaunal sample.

For deciduous teeth, the QCHM is modified:

$$\mathrm{AGE} = \mathrm{AGE}_{\mathrm{s}} - 2\mathrm{AGE}_{\mathrm{s}}\left(\mathrm{CH}/\mathrm{CH}_0\right) + \mathrm{AGE}_{\mathrm{s}}\left(\mathrm{CH}^2/\mathrm{CH}_0{}^2\right)$$

Where:

$\mathrm{AGE}_{\mathrm{s}}$ is the age of shedding of the tooth, and the rest of the terms are as above.

The QCHM has several advantages. First, it involves a straightforward measurement of remnant crown height and can be replicated by observers with low risk of inter-investigator bias. Second, it can be used on isolated teeth, which are numerous in many archaeological sites, and for which the wear stage method is less suited. Third, it is non-destructive. Klein et al. (1981: 10) recommended that the histograms displaying aggregate ages-at-death be subdivided into 10% of lifespan intervals.

Further tests of the QCHM with known-age samples of artiodactyls raised questions about terms and assumptions of the equation. Pike-Tay et al. (2000) checked the QCHM using another, relatively low-crowned cervid species, the caribou (*Rangifer tarandus*), with a large (n = 999) dental sample from the Kaminuriak herd of northeastern Canada. Pike-Tay (1995) had studied seasonality in the formation of dental cementum annuli in the same population for which date of death, and sometimes year of birth, was known from wildlife managers' notes. Using that age-at-death data, Pike-Tay et al. found that the QCHM did not predict ages at death of this relatively low-crowned artiodactyl species so well as curvilinear regressions derived from the specimens studied. They argued that the apparent source of the QCHM's inaccuracy was its assumption that the crown reached a height at or near zero at potential ecological longevity.

Steele (2006) used a larger sample of Montana *Cervus elaphus canadensis* (n = 226) than available to Klein et al. to assess the QCHM, as well as linear and regression formulae derived from her study sample. Steele found that, based on measurements of the mandibular M1, the derived regression formulae adequately estimated ages of the known-age population. However, she argued that these formulae should not simply be transferred and applied to other red deer populations because of documented interpopulational size variations that could manifest in their modal crown heights. Steele assessed whether generalized equations like the QCHM could produce acceptably accurate age-at-death estimates. Using the Montana sample, she determined that the QCHM as developed by Klein et al. did not do so. It produced consistent overestimates of ages-at-death of younger animals (Steele 2006:123–124) so that the mortality profile based on aggregate QCHM age estimates differed statistically significantly from the actual age-at-death profile.

Steele explored whether either the shape of the curve described by the QCHM or the assumption that CH reached zero at AGE_{pel} was implicated in producing inaccurate estimates. She concluded that the slope of the curve is appropriate, but that the assumption that mandibular molars' CH reached zero around a species' potential ecological longevity was not. She noted that in her known-age sample of *Cervus elaphus*, the mandibular M1 crown height reached zero in several older individuals, whereas M2 and M3 from the same individuals had substantial remnant enamel crown. She recommended estimating the age at which M1 (and other) CH actually reached zero, calculating these as y-intercepts from the quadratic regressions derived from the study sample. Steele (2006:124–125) substituted the adjusted term, AGE_{tpl}, age of tooth's potential longevity, for AGE_{pel}, in the QCHM, producing age-at-death estimates more in accord with the actual ages of the known-age sample.

Enloe and Turner (2006), working with *Rangifer tarandus* from the French Magdalenian site of Verberie, also explored the QCHM. Verberie is a short-term occupation site with reindeer young-of-the-year around 4 months of age based on dental eruption. The Verberie sample thus allowed them to explore aspects of wear stage versus adjusted quadratic age estimates with associated teeth in mandibles. Results of this study and of their exploration of wild horse crown heights suggest that quadratic-based methods should be used with caution, especially with premolars and isolated molars. Enloe and Turner also supported Steele's contention that CH_0 should be derived from one's archaeofaunal study population, showing that the unworn crown heights of Pike-Tay et al.'s (2000) list for the Kaminuriak mandibular molars were between 82% and 88% the height of the same teeth in the Verberie sample.

Motivated by a lack of concordance in QCHM age estimates on molars in tooth rows of archaeofaunal East African cattle, I checked the QCHM with North American bison, a high-crowned (hypsodont) species closely related to cattle, using known age-at-death bison mandibular dentitions (Gifford-Gonzalez 1991). The QCHM overestimated ages of animals under 5 years old and underestimated those of animals over 8 years old by as much as 40 months. A simple linear regression generally did better than the QCHM at predicting age-at-death in the bison. Although the linear regression was better at estimating age, by the time the bison were about 4 years old, age estimates derived from their crown heights by either method deviated substantially from actual ages.

I explored whether QCHM's performance might result from the assumption that CH reaches zero at AGE_{pel}. If it does not, as might be expected in more hypsodont species, the formula could produce inaccurate results, depending on how much crown height, proportionate to the original height of the unworn tooth, remains at death. To take an extreme hypothetical example, if animals living to maximum longevity consistently had 20% of their crown heights on a molar remaining rather than none, the ages of these old animals would be calculated as much younger if the formula that assumed AGE_{pel} crown height reached zero. Klein and his colleagues (1983) had explored this problem with their known-age *Cervus* sample (n = 170), investigating the deciduous fourth premolar rather than a molar, since deciduous teeth have a set age at which wear stops, the age when they are shed. They found that considerable crown height remained when the deciduous premolar was shed. At the rate of reduction predicted by their theoretical formula, the crown height would have reached zero at 33.2 months of age, well after the tooth was actually shed, on average around 26 months. Based on this, they suggested that a correction factor of 1.25 be applied to the age-at-shedding figure (equivalent to AGE_{pel} for adults) to avoid underestimating such specimens' ages (Klein et al. 1983:54).

Another potential complication involves the CH_0 term of the equation. To adjust for variation, Klein et al. (1981:15) suggested averaging crown heights of unworn teeth in archaeofaunal samples. They reasoned that variations in CH_0 around the average would produce a balance of over- or under-estimated ages from individual specimens. Ducos (1968), working with cattle in the Levant, and I (Gifford-Gonzalez 1991), working with East African cattle and American bison, further explored whether a consistent relation existed between CH_0 and the overall size of the tooth, as measured by basal breadth. If it did, then a correction factor for such size variations could be applied. Ducos and I found no correlation between crown height and basal breadth in any of the cattle samples. Likewise, no regular relationship between crown height and basal breadth was found in a sample from nearly 1000 caribou individuals (*Rangifer tarandus*) from Canada (Pike-Tay et al. 2000) or in a sample of 70 blue duiker antelope (*Cephalophus monticola*) dentitions (Joshua Peabody, personal communication, 2004). Such variability in tooth dimensions may contribute to the wide variation in crown wear over time in more hypsodont species.

To sum up, it is possible that the QCHM works better on animals of relatively low enamel crowns, such as red deer. The only known-age study of a truly hypsodont artiodactyl thus far studied is that on the bison. On logical grounds alone, it appears that the more enamel crown there is to wear over time, the greater the possibility that variation in wear rates will develop, perhaps exacerbated by the independent, inter-individual variability in tooth breadth, and hence the size of the occlusal surface of the teeth. Deniz and Payne (1982) suggested sex differences in wear rates may exist, with males wearing their teeth faster as they ate to support their larger body mass.

This raises the question how much any wear-based age estimation method is reliable, given the considerable variability inherent to mammal populations. Magnell's (2006) and Jones' (2006) documentation of problems with wear-stage ageing methods stemmed from natural variations in crown height at eruption and from individual rates of dental wear. My bison research (Gifford-Gonzalez 1991) showed that the variances in crown height of known-age animals increased with age, probably due to divergent rates of wear among these individuals. Another study of dental attrition by Benazzi et al. (2008) came to similar conclusions from a very different starting point. These researchers assessed the method using a sample of 372 first and second molars, from 157 late nineteenth- and early twentieth-century Sardinian peasants and workers from around Sassari. Using linear regression analysis, they found that only one tooth, the maxillary M1, showed a significant correlation between age and crown height. They argue that the results stem both from demonstrable inter-individual variability in initial molar crown height, despite the general genetic homogeneity of the population, and from increasing inter-individual variability in dental wear rates with age.

7.5.1 Taphonomy Again: Carnivores and Missing Dental Age Classes

Munson (2000) raised the possibility that dentitions of very young ungulates are under-represented in most archaeological samples of such animals as sheep and goats, due to taphonomic factors. This, and Munson and Garniewicz's (2003) experimental research on this topic, will be discussed in relation to mortality profiles in Chap. 21.

7.5.2 Age Estimates: Precision, Accuracy, Intrinsic Variation

After this long journey through the problems and potentials of age estimation, it is worth stepping back and asking some basic questions about the issues raised. Actualistic investigations have consistently found considerable variability within known-age populations. These include:

1. variation in sizes of any given tooth or bone, both intra- and inter-populationally, thus affecting metrical approaches to body size or tooth wear;
2. variation in ages at eruption of specific teeth, even among closely related individuals, thus affecting age estimates based upon eruption schedules;
3. similar variation in ages of epiphyseal fusion;
4. variations in overall rates of tooth wear, between right to left sides of one individual's molar rows, that among individuals within one population and that among different populations of the same species.

However inconvenient it is for zooarchaeologists seeking nice, definite age or sex determinations, this diversity is to be expected. It is the structural and behavioral variability upon which natural selection works in each generation of a species. This is what O'Connor (2006:1) meant when he said,

> Limits to the resolution of the zooarchaeological data are set in part by the limitations of our techniques, and in part by the underlying biological processes. Understanding those processes, and therefore the limits beyond which technical developments cannot take us, is a priority.

Slipshod documentation and incommensurate methods might be to blame for some of the widely varying data on ages of endochondral fusion and tooth eruption revealed in Moran and O'Connor's (1994) exhaustive review of the literature for ageing sheep, a very well-studied taxon. However, a substantial part of the "problem" arises from the intrinsic variability of the processes under study and their outcomes, as expressed in individual animals. The authors conclude their study by stressing the value of broadly sampling and studying known-age populations in the present to further understand this variation.

Moran and O'Connor's prescription is not a sophomoric, "more work needs to be done" excuse for current poor practices. Nearly every good actualistic study has shown that any given age estimation method works up to a point, but that the trait studied displays substantial variance around the modal age at which it is expressed. This is the real natural world staring us in the face.

A recent example of processes underlying this variation involves variability in horn size and form among feral Soay sheep of St. Kilda Island (Johnston et al. 2013). These descendants of domestic sheep are thought to have been on their own for about 4000 years. Individuals display a case of sustained conservation of a simple balanced polymorphism for male horn size. The genetic locus *RXFP2* (relaxin-like receptor 2) has now been identified as determining most of male horn growth and size. Males with two alleles for large horns (Ho^+Ho^+) develop large horns earlier in life, achieving social dominance among males and greater likely access to estrous females. However, they suffer energetic losses in growing and maintaining the horns, in losing opportunities to eat while keeping females with them and fending off low-ranking males, and in getting through the lean seasons. Another allele, Ho^P, exists in the St. Kilda population. Around half the males homozygous for the Ho^P allele develop more or less normal horns, but half have stunted horns and achieve low reproductive success. Nonetheless, homozygous Ho^+Ho^+ have a lower annual survival rate than do either Ho^PHo^P homozygous males or heterozygous, Ho^+Ho^P males. Johnston et al. argue that the continued polymorphism in a small population of sheep that have fended for themselves for four millennia reflects a trade-off between sexual and natural selection. While we are far from understanding all the sources of variation affecting growth and development, we this example may demonstrate that a good deal of this is intrinsic to animal populations and not due to a fault in our calibration systems.

Zooarchaeologists of my generation, and even those somewhat younger, long nurtured the hope that, if we could only "crack the code," we would find a simple, determinate means of using our archaeofaunal data to predict another datum, such as age, with good precision. This has not happened. Instead, we find strong correlations with wide variances and tendencies, as well as diversity in the expression of traits. Rather than throw up our hands in frustration at the imprecision this produces in various estimates, we should acknowledge that the problem is may not be so much with our methods as with our unwillingness to see the diversity intrinsic to organisms as it is, and to equip ourselves accordingly.

Two possible approaches lead on from this, each equally useful, depending upon the problem. One can opt for lower precision but greater certainty, and the other moves into as-yet not fully explored territory, taking more sophisticated statistical approaches to populational variability, as have the biological sciences. The starting point in either case is recognizing the difference between precision and accuracy in age estimation, and then asking how much of either is needed for the problem one wishes to address.

7.5.3 Finer Age Classes: Greater Precision

Precision refers to the ability of an estimate to be consistently replicated. A measurement can be precise, but not accurate. By analogy, one can aim for the bulls-eye on a dartboard, but throw four darts that hit within 2 cm of one another on the outer rim under the outermost concentric circle of the board. That is precise throwing, with a low range of error, but inaccurate in relation to the hoped-for bulls-eye. This is the case with some problems described for the QCHM: according to Pike-Tay, Steele, and Gifford-Gonzalez, some estimates are precise, but in relation to known ages-at-death, they are inaccurate.

7.5.4 Accuracy

Accuracy refers to how close an estimate is to the actual value of the quantity being estimated. Using the dartboard analogy again, if one's objective were to hit the center of the target, hitting the bulls-eye two times out of four throws would give 50% accuracy. Such estimates can have variable levels of precision. Combining this concept with that of precision, two darts hit the bulls-eye, another hit the rim under the outermost circle, and the last hit the wall, this represents 50% accuracy but a low level of precision. However, if the two throws outside the bulls-eye were in the ring immediately around it, this would be relatively greater precision, relative to the bulls-eye. Many of the known-age tests of different ageing methods produced somewhat accurate estimates with variable levels of precision.

7.5.5 Broader Age Categories: Greater Accuracy

One option for dealing with imprecision in age estimates is to use broad enough age classes that are sure to be accurate, even if of lower resolution in terms of calendrical age. For example, if one is working on a problem that can be addressed well with very general age categories, such as "newborn, immature, mature, aged," then most headaches of method refinement are irrelevant. In such a case, one can use a method that is relatively imprecise in producing exact calendrical age estimates but offers an extremely accurate age category.

Investigating Neanderthal foraging on the Italian peninsula, Stiner (1990, 1994) decided to work with very general age categories that wildlife management and archaeological studies had defined as useful prey age classes. She used "juvenile, prime, and aged" categories that could readily and reliably be diagnosed from dentitions. Stiner argued that these age classes, along with other lines of evidence, could offer insights into the question of hunting vs. scavenging. She displayed her age data using the ternary (triangular) plots commonly used in mineralogy (Chap. 22). Lubinski (2000), in research on North American Indians' methods for pronghorn hunting antelopes, used a similar system adapted to that species' discrete birth season and maturational calendar, with "fawn, yearling, and mature" age subdivisions. Thus, with reference to the questions they wished to investigate, both researchers traded off highly reliable accuracy in their age ascriptions against less calendrically precise age estimates, which they deemed acceptable for their research questions on population dynamics and predation.

By contrast, if one wants to explore age-based differences in managers' culling of domestic herd animals, it is probably worth opting for the most accurate *and* precise age estimation methods possible. At present, this method appears to be annular increment analysis because it extends into the adult range of life with precision and accuracy. Trade-offs in such a study may be possible; age estimates can be made using a less destructive technique with spot-checks of a sub-sample of specimens using cementum annuli analysis. Such a combination of methods would leave the bulk of specimens intact, unless or until results of spot-checks indicate serious problems with the other, less precise method. This is a case where zooarchaeological analysis must be approached, as advocated in Chap. 1, thoughtfully, with a good understanding of the strengths and limitations of various methods.

7.5.6 Statistical Realism

Finally, we can look forward to increasing use of statistical methods that may help us deal with the inherent variability of growth structures, dental attrition, and other biological traits. Researchers have attempted to describe the variability in their research materials for a long time. Carles and Meidie Lampkin (1977) expressed the variation as probability density functions, predicting how likely it would be that an individual with one incisor pair erupted would be the same age as another individual with two erupted pairs. Redding, (1981) and later, Zeder (1991) used an approach to variability in epiphyseal fusion of a given species that calculated the proportions of specific skeletal elements that were unfused, fusing, or fused within a specific age class, based on other criteria, such as bone size.

Andrew Millard's (2006) use of Bayesian statistics to estimate ages of sheep and goats represents a departure from the probabilistic approach traditionally used in zooarchaeology. Bayesian statistics is named for the Reverend Thomas Bayes, who in the eighteenth century developed what is known as Bayes' Theorem. It is an alternative to the probabilistic statistics with which most archaeologists are familiar. Rather than concentrating on falsifying a null hypothesis, it focused on estimating how likely a hypothesis is to be true, given prior knowledge about the topic studied.

More philosophical aspects of Bayes' Theorem refer to what might be called subjective prior knowledge. However, biologists and physical anthropologists – and researchers in radiocarbon dating and genomics – have taken up Bayesian statistics because it allows them to take into account concrete prior knowledge in the form of quantifiable data relevant to the likelihood of a hypothesis as part of the computational process (Koenigsberg et al. 1997). To quote Millard (2006:146) regarding its relevance to zooarchaeology:

> Traditional age estimation methods tend to treat ages as though they are exact, rather than a *distribution* of possible ages. However, no ageing method can produce exact chronological ages because individuals vary in the ages of attainment of a given developmental or degenerational stage. Even if an indicator was perfectly correlated with chronological age and all variation eliminated, the use of an ordinal scoring method (as for tooth development and tooth wear) *still* yields a distribution of ages rather than exact age because individuals enter a given stage and remain there for some period of time….

In other words, since biological processes operate statistically, a Bayesian approach accommodates this fact and even mobilizes it in calculating age estimates.

Bayesian statistics has been applied to other archaeological problems (Robertson 1999; Ortman et al. 2007), as well as to age-at-death estimation from dental eruption criteria in humans (Koenigsberg and Holman 1999; Aykroyd et al. 1999), where it showed advantages over traditional regression analysis.

Readers are recommended to read Millard's (2006) piece to explore the potentials of Bayesian approaches with regard to ageing. Such an approach would permit one to use evidence derived from independent sources, e.g. estimated age from an erupting tooth in the same tooth row, suture fusions, etc. as "prior probabilities" to set in a Bayesian computation for a specific feature's likelihood of having a certain age. An increasing number of open access statistical packages on the Internet offer researchers the possibility to apply Bayesian statistics to data. The R Project for Statistical Computing (https://www.r-project.org/), which runs on different platforms, offers a Bayesian function as part of its package.

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Part III
Basic Practical Approaches

Chapter 8
Field Recovery, Lab Methods, Data Records, Curation

Regional traditions of archaeological practice, local and national laws, and institutional requirements have encouraged a diversity of approaches to excavation, documentation, and curation. Some zooarchaeologists name their sites whatever they please; others must use a site designation system prescribed by a state or provincial government, historic preservation office, or national antiquities service. Some zooarchaeologists can chose whatever standard of documentation and curation they wish, while others must conform to contractual requirements of museums, government agencies, or archaeological societies. In the field, some zooarchaeologists use paper bags, others, plastic. Some zooarchaeologists use WindowsOS®, and some use MacOS®. Some zooarchaeologists must deposit a yearly report as a condition or continued permitting, and/or copies of their basic data and publications with a museum, government agency, or antiquities service, and some need not.

Some zooarchaeologists work in the field, directly supervising excavation and recovery of faunal remains. Others work primarily in field lab settings, analyzing assemblages produced by recent excavations. Yet others work with collections recovered earlier and deposited in museums and other research facilities after minimal or no analysis. Some zooarchaeologists have the power to direct how faunal remains are recovered and curated at the site. Some can at least interact with the project supervisor during excavation and suggest procedures that enhance recovery and conservation of faunal remains. Others working materials excavated earlier count themselves lucky to have reasonable copies of field notes and a living, mentally competent project supervisor to interview. Many zooarchaeologists – as others in their discipline – do archaeologies of archaeology, poring over scrappy, incomprehensible field notes, bemoaning lost proveniences, repairing (when possible) bones and teeth damaged by post-excavation “curation,” and figuring out what, given all the missed opportunities at documentation, mishandled specimens, and shoddy archaeological follow-up, can defensibly be said about the materials at hand. Some zooarchaeologists have their analysis of collections truncated or permanently forestalled by political developments, as did Zeder (1991), when the Iranian Revolution blocked further access the Kur Basin materials she was studying.

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Over the years, I have encountered nearly all of these cases firsthand. Quite a few demonstrate that, though there may be several ways to do zooarchaeology right, some ways are just plain wrong. In *The Early Mesoamerican Village*, Kent Flannery (1976:1) quoted Sir Mortimer Wheeler as stating that the Near East was the "land of archaeological sin," to which Flannery responded, "Such a statement could have been made only by a man who had never worked in Mesoamerica." Most seasoned archaeologists will agree that, contrary to both these eminences' pronouncements, archaeological sins are truly transgressions without borders.

Rather than attempt to document the diversity of local, national, and regional approaches to handling archaeofaunal material, this chapter reviews considerations that should guide it, offering suggestions on minimum standards of conservation, documentation, and curation – in other words, how to avoid the worst occasions of archaeological sin.

8.1 Research Design and Data Collection

Zooarchaeologists designing their research at least intuitively grasp how their theoretical perspectives condition their definition of research problems and the data they collect as relevant to those problems. These stem from theoretically grounded arguments about humans, their contexts, decisions, and actions that one find most compelling and interesting – evolutionary ecology, behavioral ecology, interpretive archaeology, Marxist or feminist approaches, etc. This turn begs the question of what types of archaeofaunal data investigators working within any given intellectual model deem useful to addressing research problems, and how they juxtapose various datasets in their arguments. Other questions emerge in this inquiry: could the data and analytic methods used in the preferred paradigm be augmented or replaced by other data or methods? One other line of questions may be asked less often: would the way one plans to recover, curate, analyze, and document archaeofaunal remains allow other researchers to use your data for different analytic purposes? Would other researchers instead have to collect data from the same archaeofaunal sample from the beginning? If so, are there ways to avoid some such duplication of effort?

Many zooarchaeologists cannot design archaeofaunal data recovery from the inception of a field project. Persons working in cultural resource management (CRM) or heritage management projects must recover and analyze samples within specific time and budgetary frameworks, often under less than optimal research conditions. However, with good standards of collection and documentation, data produced in such contexts can and has been used in scholarly research and public education – the ultimate rationale for heritage protection activities. Some regional professional societies have agreed upon central research questions and the relevant data to be collected in all archaeological projects in the region, regardless of their nature, thus assuring minimal standards of data collection. Zooarchaeologists in heritage management contexts can assure their standards of documentation by noting the data used in the research literature relevant to their region.

Zooarchaeologists using museum collections frequently must deal with archaeofaunas that were imperfectly collected and documented by modern standards, and it may be tempting to consider these materials worthless because of their limitations. Having spent most of my career working with such collections, my viewpoint is that certain issues can be addressed using such collections, and the challenge is to design research around their potential. At the very least, these collections can serve as a kind of "preliminary archaeofaunal reconnaissance" for a region, and most can offer greater research potential. Lyman's long history of contributions to the paleobiogeography and historical ecology of various mammal species (e.g. 1986, 1988, 1991, 2004, 2007) exemplifies the potential of previously excavated collections, and Stiner (1990) offers a discussion and example of working with collections recovered early in the twentieth century.

8.2 Field to Lab: Primary Recovery and Curation

It is a truism that archaeologists destroy sites as they excavate them and therefore must document as thoroughly as possible the context and disposition of materials in their original locations. This section takes a zooarchaeological perspective on this aspect of archaeology.

8.2.1 Sedimentary and Spatial Context

Reading the taphonomic history of an archaeofaunal sample, whether archaeological or paleontological, requires as much information as possible about their contexts of origin. The sedimentary matrix can testify to the range of chemical and mechanical processes affecting bones during and after deposition. Sediments can aid identifying archaeofaunal remains' relation to subtle features that may have structured human traffic and activity (Binford 1987), especially in sites lacking preserved architecture. As demonstrated by micromorphological research at the Neolithic site of Çatalhöyük (Matthews et al. 1996), it can also be informative in constructed environments.

Analysis of intrasite spatial relations of bone specimens is a time-honored practice, especially in sites inferred to result from a single occupation. Classic examples are the bison kill-butchery sites of the North American plains. At Olsen-Chubbuck (Wheat 1967, 1972), the Horner Site (Frison and Todd 1987), and other such occurrences, piece-plotting individual elements or articulated body segments permitted a step-by-step narration of the trapping, killing, and subsequent systematic primary butchery of bison. Parallel research into details of processing sometimes employs piece-plotting and refitting bone element fragments across a site, as was done at the Pliocene site of FxJj20, East Lake Turkana, Kenya (Bunn et al. 1980). Todd (1987) took the spatial approach further, combining precise spatial plots of elements and body segments with a detailed metrical and morphological matching of bilaterally symmetrical bones of the bison body, permitting reconstruction of the disassembly of individual animals. Enloe and David (1992) pursued a parallel analytic approach at the Magdalenian reindeer hunters' encampment of Pincevent in the Seine River basin not far from Paris; by "refitting" individual animals, they were able to trace the social subdivision of animal carcasses among the excavated dwellings (Chap. 25). Waguespack (2002) investigated the nature of carcass subdivision and sharing with this strategy at a historic Nunamiut Inuit campsite (Chap. 25). All such analyses were done before Total Station Mapping (TSM), which speeds spatial documentation of three-dimensional coordinates.

Such meticulous spatial analyses of archaeofaunas are possible only under certain circumstances of preservation and deposition. A preponderance of skeletal elements must be identifiable and measurable and deposited over a relatively short span. Other cases do not permit a piece-plotting approach to analysis. Midden deposits from villages, towns, and cities can contain tens to hundreds of thousands of specimens, potentially representing hundreds of individual animals, parts of which may have been redistributed and discarded on a citywide scale and often were reworked by later construction in ancient times. These occurrences require other spatial documentation strategies. Commonly, specimens may be documented only to excavation unit or to feature (e.g. Zeder 1991). This involves trading off precision of spatial detail against gaining a larger sample, and being able to search for robust patterning in a large dataset.

I analyzed the archaeofauna from a site with very dense artifact and bone concentrations, the Holocene pastoralist-hunter Prolonged Drift (SAES coordinate number GrJi1), excavated in central Kenya in 1969 (Gifford et al. 1980). From about 18 m^2, excavators recovered over 165,000 bone specimens and more than 220,000 lithic and ceramic specimens (Fig. 8.1). Investigators began by piece-plotting all specimens, but, to make any headway at all in exploring the extent and boundaries of the accumulation, they switched to documenting each specimen's location to the quarter-m^2 by 5 cm vertically. They traded off point-provenience data analyses against obtaining a sense of the spatial scope of activities creating the deposit.

8.2.2 Influence of Recovery Methods

Another, parallel trade-off is that between excavation time and comprehensive recovery of small specimens. Recovery of microfauna, smaller fish, amphibians, reptiles, birds, and mammals requires very small screen size (≤3 mm or 1/8 in) to sieve excavated matrix, as well as wet screening and/or flotation methods. Experimental studies have demonstrated that recovery of taxa can be strikingly different with different mesh sizes (Davis 1987; Payne 1972). Screen sizes larger than 1/8″ (4 mm) result in substantial losses of elements from smaller species or from smaller individuals of vertebrates of variable sizes (Payne 1972; Shaffer 1992; Stahl

Fig. 8.1 Bones, obsidian and other debris in a quarter m^2 at the Kenyan site of Prolonged Drift (GrJi1), near Lake Nakuru, Kenya (Photograph by the late Glynn Isaac and in possession of the author.)

1992, 1996; Shaffer and Sanchez 1994; Nagaoka 1994; James 1997; Zohar and Belmaker 2005). Reitz and Wing (2008: 154–156) give an excellent example of this problem. In the early Spanish archaeofaunal sample from St. Augustine, Florida, using 6 mm (~1/4″) mesh screen would recover a just under 16,000 specimens, with mammals comprising over 87%. Using 3 mm mesh would recover another 1960 specimens, in which mammals comprised only 1% of the assemblage and fishes nearly 97%. Reitz and Wing (2008:148–150) also report that flotation is the only strategy for obtaining very small fish species, and that taxonomic abundances can be skewed substantially by size-selective recovery. For representative recovery of archaeofaunal taxa, quite a small screen size is thus optimal.

However, such methods are time- and labor-intensive and sometimes rendered difficult if not impossible in the field clayey soils or lack of sufficient water for wet-screening or flotation. Like paleoethnobotanists and other archaeologists seeking microdebris, zooarchaeologists must trade off loss of that level of recovery for the excavated site as a whole against a set of controlled samples recovered for later, fine screening. These normally are time-honored methods of core or column sampling (Casteel 1970; Hester et al. 2009) that remove the entire contents of either a rectilinear subunit of a regular excavation unit (column) or an augured core of specified part of a unit or feature. These samples are subdivided by vertical provenience and can be wet-screened with 2 mm or even smaller-gauge screen or floated for total recovery of the sample contents in another setting (see also Lyman 2005). We received such an archaeofaunal flotation sample from a recently excavated site just north of the Monterey Bay, California. Sorting these under binocular microscope, the doctoral student and archaeoichthyologist Cristie Boone (Albion Environmental) isolated many bones of sardine- and herring-sized fishes, which had never before been reported from coastal sites in southern San Mateo County (Gifford-Gonzalez et al. 2006).

The core/column technique also requires that a sampling strategy be devised. Input from zooarchaeologists is helpful in designing appropriate strategies, as random sampling may not be optimal for specimen recovery. Parallels exist in other archaeobiological fields: based on their understanding of plant processing practices, paleoethnobotanists have developed tactics for sampling diverse locales for macrobotanical remains. Features such as hearths, storage pits, and threshing floors are often slated for sampling in agricultural settings (Dennell 1974; Pearsall 1989; Reddy 1997). Sampling for smaller faunal remains can be guided by similar expectations, including the simple prediction that very small bone and other faunal debris may be recovered from substrates near hearths and other food preparation areas (see Chap. 15). Lyman (2012) cautioned that experimentation showed that screen size should be selected with prior estimates of local microfaunal bone size in designing recovery strategy.

8.2.3 Cleaning

Cleaning of faunal materials involves multiple risks of bone surface modification or other forms of specimen damage. Brushing dirt-covered bones with stiff-bristled brushes can add surface modifications to bone in the form of pseudo-cut mark scratches (Bromage 1984). Water or additives such as dilute detergents may affect specimen integrity or complicate their use in dating or ancient DNA (aDNA) analysis. Other forms of cleaning have their risks. Preparators' tools used to remove concretions can mark bone in ways that mimic ancient human intervention (Shipman and Rose 1983; White and Toth 1989). If poorly managed, dilute acids intended to remove concretions from bone surfaces can dissolve those surfaces as well. Ultrasonic baths can remove concretions and dirt but involve some risk to delicate specimens, as can air scribes. Probably the most common risk during cleaning is loss of provenience. In field situations and laboratories with multiple workers, protocols are required to assure consistent association of provenience data with as specimens move through cleaning.

8.2.4 Preservation and Conservation

Preserving organic materials as they come out of the ground is among the most variable of field recovery problems. Depending on the chemistry of the sedimentary contexts from which they are excavated, bones, shells, scales, and other animal remains may resist degeneration or be very vulnerable to distintegration. Use of stabilizing media and cleaning procedures should be rethought in light of recent developments dating and genomic analysis. Radiocarbon determinations on bone and shell require that at least some of an archaeofaunal sample be protected from contamination by modern carbon. Matisoo-Smith and Horsburgh (2012) recommended that specimens slated for aDNA not be washed.

Bones in intermittently and constantly moist, acidic environments may have lost most of their calcium apatite, with only remnant collagen, which is vulnerable to disintegration on drying. Special tactics are required on-site to conserve them. At the Mesolithic site of Star Carr (Clark 1954), a vacuum chamber was used to perfuse with preservative and stabilize red deer bones recovered from an acidic peat bog. Soil processes and other pre- and post-depositional taphonomic may leach collagen and calcium from bones rendering them more fragile than fresh bone. Clayey soil can filter into cracks in bones, and subsequent wetting of the sediments can cause the clay to expand in the cracks, in essence exploding them in the matrix and presenting challenges to recovering them as integral units. Other specimens may be encrusted in calcium carbonate concretions or other chemical precipitates to the point that taphonomic modifications to the bone surfaces and cannot be documented until the deposits are removed.

Recounting many methods for coping with these and other site-specific conservation problems is beyond the scope of this book. Readers should see Hester et al. (2009) for an introduction, as well as online information on preservatives and their solvents by Hamilton (1999). Conservation in the field should avoid tactics that will obscure the morphology and surface modifications to elements, consistently and pervasively alter their chemistry, or otherwise stand in the way of later laboratory analysis. To paraphrase the well-known medical ethic, when trying to preserve a specimen, the field crew should first, do it no harm.

Some specimens do require stabilization in the field, but permanent preservatives should be avoided. These may obscure the bone surface's traces of human and nonhuman actors, and removing them involve toxic chemicals and possible loss of the original bone surface. I had to abandon seeking all but the grossest bone surface modifications in a sample of nearly 5000 identifiable specimens from one early East African pastoralist site because a polymethacrylate emulsion had been liberally applied in the field to nearly every specimen when most still had considerable soil, roots, and even tiny obsidian flakes on their surfaces. Efforts by lab technicians in the Kenya National Museum and myself in 1990 to find a solvent for the layers of preservative and dirt were fruitless, and some of the chemicals we used were probably neurotoxic. From Hamilton's (1999) webpage on adhesives and consolidants, I now know that we'd have experienced more solvent success, had we added toluene, a toxic aromatic hydrocarbon, to our already dangerous cocktail. Acetone softened but did not dissolve the preservative layer. When I tried to gently peel the gummy preservative layer off specimens, the outer layer of bone came off with it, and I desisted. I decided that this assemblage could testify only to less fine-grained levels of processing activities. The same assemblage presented other related problems: field technicians unschooled in osteology had used the preservative as glue, sometimes joining bits from different elements and species. If one cannot dissociate such them in the lab, one is literally stuck with specimens of albeit momentarily amusing but problematic hybridity.

Such complications can be avoided by cleaning specimens better in the field and by stabilizing only those that truly need it with water-soluble preservatives. Mistakes made in the field can literally be dissolved in the lab. Wheat (1972) stabilized the Olsen-Chubbuck bison bones in the field with a dilute solution of Borden's Elmer's Glue®, then produced from casein, a dairy product, which he reported could later be removed by soaking specimens in water. Aside from appreciating the irony of applying a bovine-derived preservative to wild bovine bones, readers are advised that, several decades ago, Elmer's Glue-All® shifted to a polyvinyl alcohol resin emulsion. While the manufacturer cites water as a solvent (Hamilton 1999), some of us have found the glue to be less water-soluble than anticipated.

It is relatively straightforward to develop field procedures that avoid many such problems if zooarchaeologists can communicate with persons excavation and initial curation in the field, if they themselves cannot be involved directly. Protocols for recovering and handling faunal remains can be developed and circulated to minimize damage to vertebrate remains.

8.2.5 Provenience Information Management

Once archaeological specimens are recovered from their sedimentary contexts, initially cleaned, and stabilized, they are grouped and handled according to protocols that can vary from one excavation – or one zooarchaeologist – to another. The traditional practice of putting everything from an excavation unit level in one bag labeled with provenience information and storing it for sorting and analysis at a later date is still common. But field labs, where preliminary sorting and initial analysis and data transcription take place, are now more common. Project-specific trade-offs again present themselves. Costs of fielding and providing analytic facilities to a set of specialists may sometimes be justified and other times not. Likewise, having only semi-skilled workers sort and bag finds from excavation units into material categories (ceramics, lithics, bones, shells, etc.) must be weighed against the risks of inadvertent damage to delicate remains during sorting or transport.

8.2.6 Labeling

Whatever the distance from the field to the lab, information regarding specimens' source coordinates must travel with them. Provenience data may be applied to the specimens themselves, be attached to specimens by paper tags that ride with them inside bags, be written on the outsides of paper or plastic bags, or even attached via scanning tags. In the U.S., some federal government agencies, state agencies, or state historic preservation offices recommend curation standards for the end products: acid-free paper products, plastic bag thickness, specific forms, electronic database formats, and so forth. These standards can be met, at a relatively low cost, in much of the developed world but are much more difficult for even major institutions in less developed countries to meet. I personally believe that foreign researchers in such regions have an ethical obligation to support the long-term curation and maintenance of the collections they use by investing in upgrading their physical curation to reasonable standards.

A longstanding tradition in archaeology favors applying provenience or catalogue numbers directly to specimens. However, this may not be advisable for specimens to be analyzed for bone surface modifications. A taphonomic corollary of Murphy's Law predicts that the only cut mark or other diagnostic trace of an actor on a specimen will invariably be transected by a neatly lettered specimen number, often written on a thick application of white paper correction fluid and topped off with a layer of clear nail polish. If a specimen is large enough, one can prudently avoid loss of provenience by writing catalogue numbers on it, a task best done by someone who knows enough about zooarchaeology to avoid bone surface modifications. In elements so small, or so modified, that writing on them would seriously compromise recoverable taxonomic and taphonomic information, provenience information is best attached on a tag or card associated with the specimen.

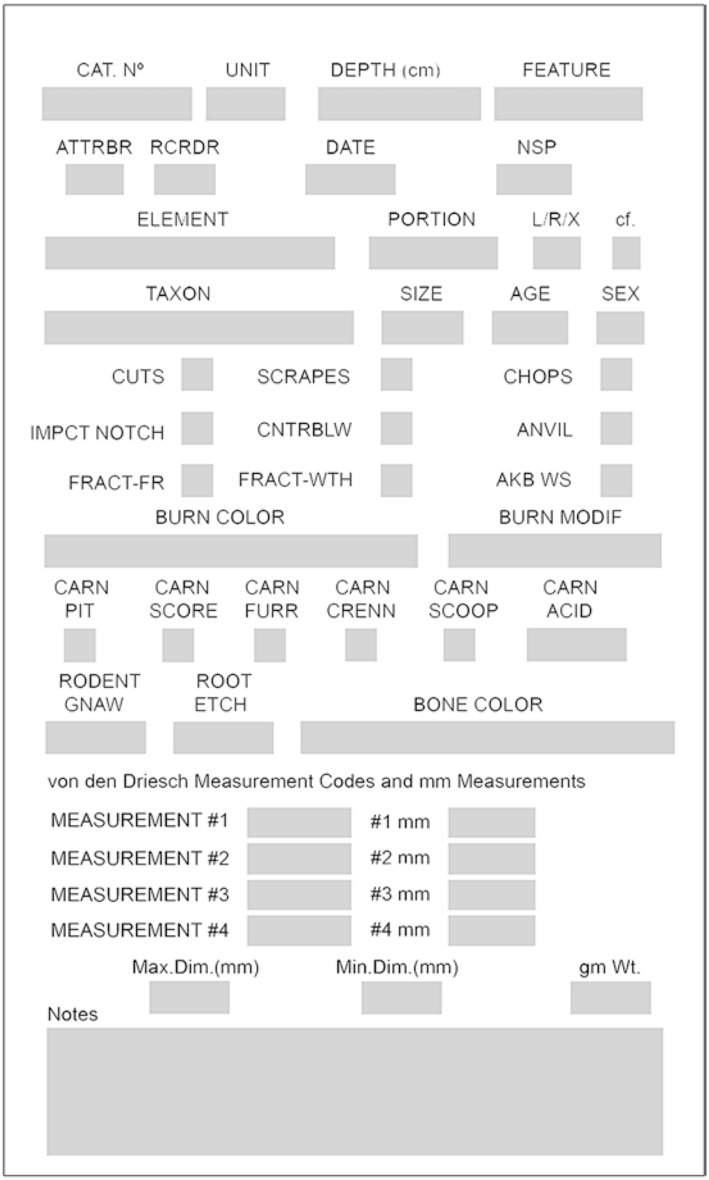
In my lab, we lacked the person-power to directly label thousands of specimens from a variety of excavators. Each potentially identifiable specimen received a specimen card with a randomly assigned catalogue number (produced by an automatic number stamper) and its own resealable bag. Printed on the specimen card are all the data fields that will eventually be entered into the site database. Starting with provenience data, the card accumulates progressively more information (Fig. 8.2). Less identifiable and nonidentifiable specimens are grouped in bag lots (Chap. 9).

8.3 Specimens into Data: Analytic Considerations

The next phase of zooarchaeological analysis is usually to sort and identify specimens to the greatest level of specificity possible, and to record bone surface modifications and other types of postmortem modifications.

8.3.1 Element and Taxonomic Identification

For final taxonomic identification, faunal analysts normally opt to work with comparative bone specimens rather than simply with drawings or other representations of animal remains (Parmalee 1985). As noted earlier, this is due in part to the fragmentary nature of zooarchaeological specimens, in which only a small segment of an element may be present. Identification is therefore sometimes a matter of seeking out a range of probable elements and species and then carefully searching for the closest possible morphological or metrical match.



CAT. N° UNIT DEPTH (cm) FEATURE

ATTRBR RCRDR DATE NSP

ELEMENT PORTION L/R/X cf.

TAXON SIZE AGE SEX

CUTS SCRAPES CHOPS

IMPCT NOTCH CNTRBLW ANVIL

FRACT-FR FRACT-WTH AKB WS

BURN COLOR BURN MODIF

CARN PIT CARN SCORE CARN FURR CARN CRENN CARN SCOOP CARN ACID

RODENT GNAW ROOT ETCH BONE COLOR

von den Driesch Measurement Codes and mm Measurements

MEASUREMENT #1 #1 mm
MEASUREMENT #2 #2 mm
MEASUREMENT #3 #3 mm
MEASUREMENT #4 #4 mm

Max.Dim.(mm) Min.Dim.(mm) gm Wt.

Notes

Fig. 8.2 Example of data card placed in bags with specimens in Gifford-Gonzalez zooarchaeology laboratory through 2012. Card is filled in successively as analysis proceeds, and data entry is made into virtually identical fields. See text for details

If more than one similar-sized species of a given zoological subfamily, family, or order possibly exists in a sample, one must refer to comparative specimens from all such species to make final taxonomic diagnoses. For some closely related and commonly encountered species, such as domestic animals, either morphological or metrical distinctions are described in the literature, as is the case with sheep and goats (Payne 1969; Prummel and Frisch 1986; Rowley-Conwy 1998; Boessneck 1969; Zeder and Lapham 2010; Zeder and Pilaar 2010). However, in many cases, zooarchaeologists may have to establish their own reference criteria, again on the basis of comparative specimens of known species.

Zooarchaeologists must sometimes build their own reference collections, either because comparative collections in museums or other institutions are too distant to consult regularly or because no comparative collections exist for the species in question. Agricultural stations and colleges, local markets, road kills, local inhabitants in areas where hunting is common, and beachcombing can provide animal bodies, although collectors should fully inform themselves about applicable laws and collecting permits. Preparation of animal bodies into comparative specimens requires no specialized equipment but requires knowledge of and adherence to health and safety standards, as well as knowledge of how different types of bone respond to heat or enzymatic treatment. Preparations can range in palatability from a carefully dissecting a poached salmon dinner to the grisly maceration or boiling operations that can make members of the zooarchaeological community outcasts at home and abroad.

Regarding taxonomic identification, Butler and Lyman (1996) made several recommendations for zooarchaeological reports. While analysts need not describe the basis of their identifications of common species, they should present their rationale for taxonomic ascription in the case of a rare species, or of new criteria for identification of closely related or rare species. They present conventions for such descriptions derived from the paleontological and zoological literature, involving morphological and metrical descriptions of distinctive dental, cranial, or postcranial osteological features of the species in question. Excellent zooarchaeological examples can be found in Grayson (1984).

I recommend keeping a lab log or diary, preferably digital, used by everyone working on an assemblage, to record important observations on specimens or decisions about how and why to record certain data. This might include such novel taxonomic ascriptions as discussed by Butler and Lyman. I also record unusual modifications for which no data field exists in my database, but which are recorded in the “Notes” section of individual specimen cards and the database. Any major decision made during analysis that affects descriptive variables (e.g. adding another color category from the Munsell® system to the database) is recorded, with its rationale, as well as informal notes on redundancies in types of modification of a given taxon or element. Because every assemblage differs, any given analysis may require modifications to data fields or variables employed. In working with the Adrar Bous, Niger, early pastoral (c. 5000–2500 B.C.) archaeofauna, I noted the dissolution of dentine from bovid teeth, to the extent that the tooth enamel sometimes collapsed upon itself, something I had never seen in more than 30 East African archaeofaunas

(Gifford-Gonzalez and Parham 2008). After documenting about 25 such specimens in the "Notes" field of specimens cards and our FileMaker® database, I decided this was such a common and interesting occurrence as to justify creating a new data field, "Dentine Loss," so that I could record this aspect of the assemblage on a simple qualitative scale, from "none" to "extreme." The decision and the variables settings went into the Adrar Bous lab log, and text from the log was later incorporated into the final write-up of the assemblage. The effort invested in writing a clear methodological rationale for a new procedure in the log pays off sometimes months or years later, when this can often be copied directly into the methods section of a monograph chapter or journal article.

8.4 Data to Database: Recording Information from Specimens

Most zooarchaeologists use computers to create and manipulate archaeofaunal databases. Rapid advances in hardware and software capabilities, especially personal computers, Total Station mapping, prompt-based data input systems, relational databases, and sophisticated plotting and graphing capabilities impel the continued emergence of new systems of recording and managing zooarchaeological data. It is most prudent, therefore, to avoid discussing specific systems that will soon be outdated and concentrate instead on what data management should do relative the ultimate goals of zooarchaeological analysis.

Systems for managing zooarchaeological data are numerous and widely published, and the best advice I can give is to examine a range of these systems and their flexibility before either committing to one in particular or trying to devise one's own. Early examples include Meadow's "Bonecode" (1978), Campana and Crabtree's "Animals" system (1987), Klein and Cruz-Uribe's (1984) database system, that developed by myself and Crader (Gifford and Crader (1977); Gifford-Gonzalez and Wright 1986) and subsequently adapted to other settings (Parker and Kaczor 1984). The cloud-based Ossobook archaeofaunal database (http://xbook.vetmed.uni-muenchen.de/wiki/OssoBook), developed by a consortium of German and Swiss institutions, permits interassemblage comparison as well as recording. Readers are also referred to Reitz and Wing's (2008: 153–250) discussion of their primary and secondary data recording methods.

Minimally, a system should permit entry of specimens' data without having to physically pre-sort specimens by provenience, osteological or taxonomic order. A good system will be easy to use at the inputting end, using menus for the element and Linnaean names recorded on specimen tags, thereby minimizing keystroke errors and allowing less zooarchaeologically skilled people to do data entry. It should readily produce osteologically or taxonomically ordered tables, without involving additional human inputs of element and taxon names, and facilitate estimates of basic zooarchaeological counting units (Chap. 10).

Marean, Cleghorn, and other former members of Marean's Arizona State University laboratory developed a FileMaker® database format that is now widely used (Fig. 8.3). It offers visual templates of elements of various taxa to facilitate logging the osteological landmarks preserved on individual specimens. These in turn engage with an Excel®-based pivot table estimation of number of identifiable specimens (NISP) and minimum number of individuals (MNI), abundance measured to be discussed in Chap. 10. The advantages of a system that incorporates osteological landmarks will be discussed further in Chap. 10,

I created a custom FileMaker® relational database with lookups for the element, portion, and taxon numeric equivalents for originally developed by Gifford and Crader (1977) to produce osteologically and taxonomically logical sorts of large datasets. The data entry view uses pull-down menus that allow persons with little familiarity with osteology or animal systematics to enter data from lab specimen cards (Fig. 8.4). Sorts and tallies of NISP can be run in the application, and tab-delimited data can be exported for statistical analysis and other aggregation. The database structure lacks the built-in landmark system of the Marean et al. database structure. As the case with other FileMaker® products, the database is compatible with WindowsOS® and MacOS® operating systems, and it has also been adapted to Microsoft Access®.

8.4.1 Data and Specimen: A Necessary Relationship

One other form of data control has seldom been discussed in zooarchaeological publications: associating data generated from a specimen with the specimen itself in its permanent curation and storage location. In most sciences, the standard by which scholarly research is judged is its replicability. Publications of research results are supposed to present enough information about materials and methods that another researcher can reproduce the experiment and compare results of the original with their own replication. It allows a researcher's results to be checked and inferences drawn from those findings to be assessed by the community of practitioners.

Today, zooarchaeologists can post their datasets on a number of institutional or nonprofit websites, which is a great step forward toward ensuring access to information and a certain level experimental replicability. However, doing so does not permit other researchers to assess the accuracy of the initial element, portion, side, and taxon determinations, age estimates, observations on taphonomic modifications, metrical data gathered, and any other determinations made by the archaeofaunal analyst. This is the first step in assuring experimental replicability, and in many scientific fields, even new ones, well known standard procedures are followed and are expected to be stated explicitly in scholarly articles. Thus far, no such standards exist across zooarchaeological practice, despite the fact that simple *and* more technologically sophisticated methods for doing so exist. In zooarchaeology, other researchers seldom attempt a wholesale re-analysis of a faunal assemblage on which another has worked. However, one's *specimen identification and descriptions of*

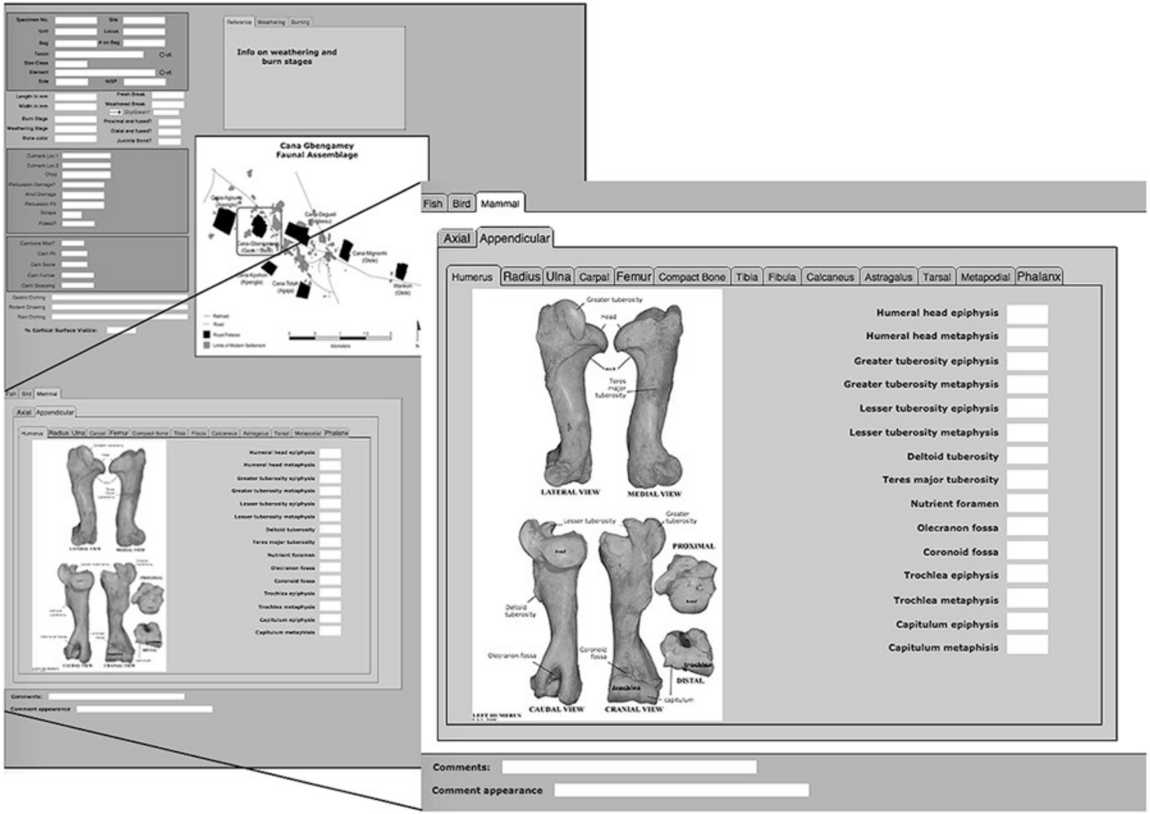
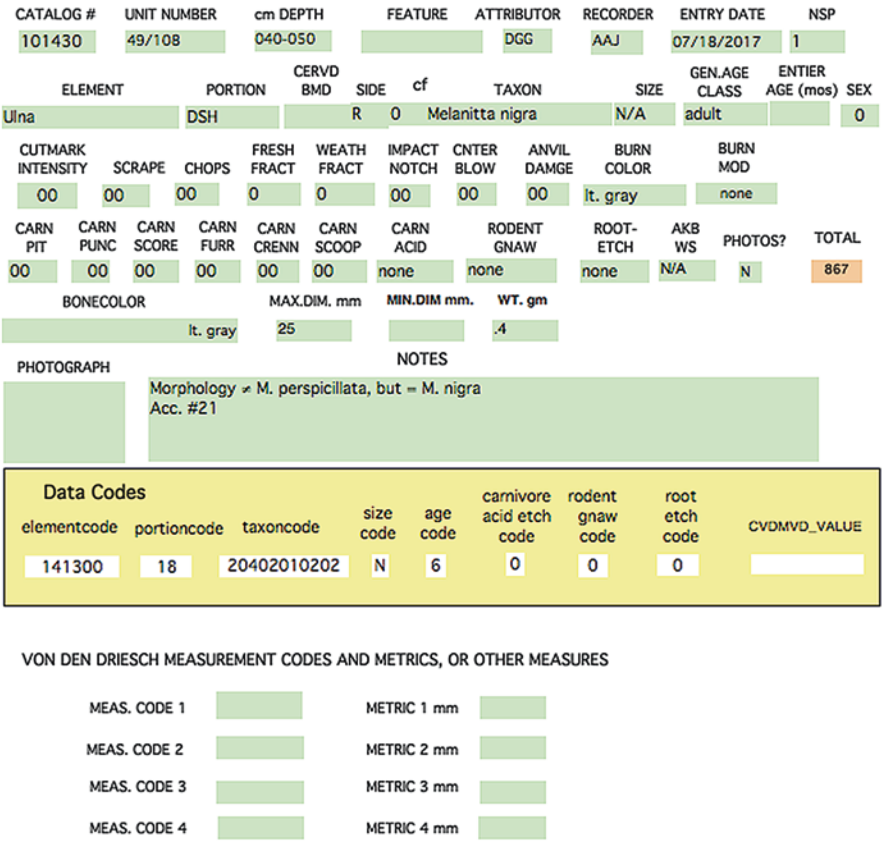


Fig. 8.3 Illustration of an example the Marean-Cleghorn FileMaker® recording system recording Anneke Janzen's analysis of the Cana Gbengamey (Bénin) archaeofauna, with the landmark section enlarged for clarity (Illustration by the author, database used with permission of Curtis Marean and Anneke Janzen.)



CATALOG #	UNIT NUMBER	cm DEPTH	FEATURE	ATTRIBUTOR	RECORDER	ENTRY DATE	NSP
101430	49/108	040-050		DGG	AAJ	07/18/2017	1

ELEMENT	PORTION	CERVD BMD	SIDE	cf	TAXON	SIZE	GEN.AGE CLASS	ENTIER AGE (mos)	SEX
Ulna	DSH		R	0	Melanitta nigra	N/A	adult		0

CUTMARK INTENSITY	SCRAPE	CHOPS	FRESH FRACT	WEATH FRACT	IMPACT NOTCH	CNTER BLOW	ANVIL DAMGE	BURN COLOR	BURN MOD
00	00	00	0	0	00	00	00	lt. gray	none

CARN PIT	CARN PUNC	CARN SCORE	CARN FURR	CARN CRENN	CARN SCOOP	CARN ACID	RODENT GNAW	ROOT-ETCH	AKB WS	PHOTOS?	TOTAL
00	00	00	00	00	00	none	none	none	N/A	N	867

BONECOLOR	MAX.DIM. mm	MIN.DIM mm.	WT. gm
lt. gray	25		.4

PHOTOGRAPH	NOTES
	Morphology ≠ M. perspicillata, but = M. nigra Acc. #21

Data Codes

elementcode	portioncode	taxoncode	size code	age code	carnivore acid etch code	rodent gnaw code	root etch code	CVDMVD_VALUE
141300	18	20402010202	N	6	0	0	0	

VON DEN DRIESCH MEASUREMENT CODES AND METRICS, OR OTHER MEASURES

MEAS. CODE 1		METRIC 1 mm	
MEAS. CODE 2		METRIC 2 mm	
MEAS. CODE 3		METRIC 3 mm	
MEAS. CODE 4		METRIC 4 mm	

Fig. 8.4 Screen shot of the author's FileMaker® relational database. Data fields correspond to those in Fig. 8.2. Fields in the "data codes" box are automatically reported numeric equivalents of element, portion, and taxon identification entries, according to Gifford and Crader (1977), plus numeric equivalents for some identification fields that facilitate anatomically and taxonomically logical sorts of entries. For elements too fragmentary to measure, von den Driesch fields are left blank (Illustration by the author)

taphonomic evidence should be readily accessible to assessment by others. Gobalet (2001) recommends that faunal reports stipulate the reference collections used for species attributions and the location of permanent storage of the collection analyzed – as a means of assuring the "experimental replicability." See also Butler and Lyman remarks in Chap. 10.

A product-focused approach demands design of analytic and data storage systems that reveal as much as possible about individual specimens' histories and, ultimately, about the redundancies and aggregate patterning in our assemblages. The simplest way to assure this is to attach the same data that goes into a research database to a bag, tag, card, or even a digital code that remains with the specimen and links to an online database. Other researchers can thus spot-check the competence of another researcher on a case-by-case basis.

However, some zooarchaeologists simply dump each specimen back with others into a unit/level bag once they have recorded their data. It's certainly quicker to toss specimens back into their original bags than to record the data twice, once on a record that remains with the specimens and once in a database. However, whether or not done with that intention, it disguises the researcher's first steps in producing a dataset. Other scientists are left to accept or reject the validity of published observations or even posted datasets on faith.

Basic data attached to the specimens themselves are not only a form of ethical practice but also as a form of insurance against the loss of digital records or unexpected truncation of analysis. I am not the only researcher to have had a computer stolen during fieldwork: the phrase "portable laptop" takes on a whole new meaning after a mugging. In my case, the data on its hard drive were backed up elsewhere, now quite feasible with "cloud" based storage technologies. However, in the worst-case scenario, aggregate site data could have been reconstituted from the specimen tags in the museum collections because I had made a practice of recording all information on them. Archaeologists also may die long before they expect to, leaving their analyses incomplete. In the case my mentor, who passed away at age 47, each archaeological specimen he analyzed had the same information attached to it as were in his interim notes at the time of his death. Under the difficult infrastructure conditions that exist in some parts of the world, functional computers or even a reliable electrical supply may not be assured to museum collections managers and curators or visiting researchers wishing to check a site's archaeofaunas. In such cases, specimen data cards themselves can be hand-sorted to produce summary archaeofaunal tabulations.

As curator of our local archaeology archives, I have had to cope with the problem of missing identification data. The zooarchaeological sub-contractor for several development-related mitigation project collections deposited with our archives chose to write only the animal genus on specimen tags, despite presenting site report summary tables that included Minimum Number of Individuals. That statistic would have required knowing the element identification and from which side of the vertebrate body a bilaterally symmetrical element derived (Chap. 10). To make this collection useful to visiting researchers, graduate students, and myself, I re-identified over 5000 such "previously identified" specimens to element, portion, and side, essentially redoing the analysis. This is not really what I had in mind when I advocated "experimental replication" in zooarchaeological analysis.

In my own laboratory, we have experimented with two data recording approaches for specimen cards. The first was filling values into preprinted cards data fields on that match fields in our FileMaker® database (Figs. 8.2 and 8.3). When all the fields are filled and definitive identifications are checked, these data are entered into the database. The second involved making less formal notes on relevant data on blank acid-free cards, entering these data into the database, and then printing a self-adhesive label to put on the blank side of each card, which presented all the information in a neatly typed format. Since less skilled lab interns do most of the data entry, I have opted to use the defined-field data card shown in Fig. 8.2, since it allows them to relate the hand-written data in each card's fields to fields with pull-down menus in the FileMaker® database. Another approach is now possible: printing a digital code such as a Universal Product Code (UPC or barcode) or a Quick Response (QR) code that can be inserted with a specimen and linked to institutional computers or online databases. When inserted with a specimen, these would allow anyone with a smartphone to access individual specimen data, or perhaps call for a print of a dataset. Some of us older traditionalists may prefer the legibility of a paper label, but this is a quicker means of attaching data to specimens. In the developing world, this is a realistic alternative for museum and curation facility management, as one can expect technologically savvy staff. Mobile phone and tablet use has surged where landlines never existed, and people in the global South used apps for online banking well before it became widespread in the global North.

8.5 Lab to Archive: Curation Considerations

Having served as curator of our university's central coastal California archaeology collections for about 40 years, I am aware of the value of well-curated materials to visiting researchers or students working on specific projects. Few zooarchaeological texts have discussed this matter, and Reitz and Wing's (2008) discussion of curation is in an appendix. Sullivan and Childs (2003) noted the longstanding tendency of field archaeologists to regard repositories as "dumps" rather than the repositories of well-prepared materials, whether analyzed or unanalyzed, that have future research functions.

For zooarchaeological materials, just as for other artifactual materials, data attached to specimens are essential to the curation and further research, as well as being *the* fundamental bases of experimental replicability in zooarchaeology. Practices acceptable when the goal of archaeofaunal analysis was a list of species may now be inappropriate for detailed, product-focused taphonomic analyses of bone surface modifications. We now have technological infrastructure to facilitate such practices at relatively low cost and time investment, and thus have little excuse not to build in experimental replicability from the ground up.

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Chapter 9
Identification: Sorting Decisions and Analytic Consequences

Zoologists traditionally have focused on complete skeletons, and even paleontologists show a preference for more or less complete osteological elements when distinguishing species. Zooarchaeologists, by contrast, expect that most of their specimens will be fragmented due to human handling and other taphonomic processes. They also expect that valuable information about human handling and site formation is recoverable even from less identifiable specimens. Thus, from the initial sorts of an archaeofaunal sample, specimen identifiability is assessed, and the balance of one's analysis can follow upon the decisions made at this point. Because analysts make this distinction differently, how one decides to exclude specimens from further analysis can ultimately determine the structure of one's data on element frequencies and even taxonomic abundances, possibly affecting inter-analyst comparability. This major, albeit seldom discussed, methodological issue merits treatment in some detail in this chapter.

9.1 Levels of Identifiability: A Multidimensional Issue

The analyst's first task is to sort through archaeofaunal materials from a unit and level. If one empties out a typical level bag containing only fauna, one may see a few whole bones, bone fragments, teeth whole or broken, and, depending on the area sampled perhaps some molluscan shell. Some specimens, such as rodent incisors, are immediately recognizable as belonging to a certain taxonomic order. Depending on one's familiarity with the regional fauna, certain elements of some species, like a warthog tooth, are immediately identifiable to species level. Other fragments may be attributable to element on the spot but require comparative specimens for species attribution. One may recognize a distal radius of a medium-sized artiodactyl, or the third phalanx of a raptorial bird, but these will require further checking against morphologically similar and like-sized species known to inhabit the region studied. Other bits of bone are recognizable according to their body

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Table 9.1 Some examples of the interaction of differing levels of taxonomic versus osteological identifiability (ID)

Osteological ID	High Taxonomic ID	Medium Taxonomic ID	Low Taxonomic ID
High *Example*	Cervical 3 Thomson's gazelle	Cervical 3 Small bovid	Cervical 3 Medium mammal
Somewhat lower *Example*	Cervical fragment Thomson's gazelle	Cervical fragment Small bovid	Cervical fragment Medium mammal
Considerably lower *Example*	Vertebra fragment Small bovid	Vertebra fragment Small artiodactyl	Vertebra fragment Medium mammal
Lowest *Example*	Cancellous fragment Medium mammal	Cancellous fragment Medium mammal	Cancellous fragment Mammal size indeterminate

region, for example a fragment of vertebra or a 2-cm length of long bone shaft. Still other fragments, however, are simply recognizable as bones of mammals, of birds, of reptiles, amphibians, or fishes. Finally, some fragments are so ambiguous that one might resort to microscopic examination (or the notorious touch-it-to-the-tongue test – bone usually sticks) to determine if it even is bone. The foregoing descriptions distill the two intersecting continua of identifiability: osteological identifiability, on the one hand, and taxonomic identifiability, on the other. This can be represented in tabular form, showing how high-to-low levels of osteological and taxonomic identifiability interact to produce different identification outcomes (Table 9.1).

Remarkably few methodological articles or zooarchaeological reports have discussed the criteria involved in distinguishing an identifiable from a nonidentifiable specimen. An exception is Driver's (1992) excellent piece, republished with comments by other zooarchaeologists, as well has his own reflections 20 years later (Driver 2011). The issue was explicitly addressed by Klein and Cruz-Uribe (1984), Morales Muñiz (1988), Reitz and Wing (2008), and Zeder (1991), demonstrating that a diversity of opinion exists among zooarchaeologists regarding criteria for cutoffs between these categories. One zooarchaeologist's "unidentifiable fragment," excluded from further examination early in analysis, may include diaphyseal fragments recorded as "Medium bovid tibia" in another's analysis. Marean et al.'s (2004) discussion of diaphyseal fragments in palaeolithic assemblages presents a good overview of these divergences' analytical implications.

9.1.1 *Factors Influencing Identifiability*

Binford and Bertram (1977) asserted that there is no such thing as an unidentifiable bone. From the viewpoint that any bone fragment does ultimately derive from a specific bone in a specific animal of a specific taxon, it is theoretically possible that any specimen could be identified. However, in practice, most analysts are more than willing to put a proportion of fragments in a "nonidentifiable" category.

Preliminary sorting and analysis into potentially identifiable and nonidentifiable is influenced by a variety of factors. These include:

1. The abilities of the analyst;
2. the extent of specimen fragmentation by human action or other processes;
3. the screen size or other recovery methods used in obtaining the sample;
4. the likelihood of encountering two or species of similar size and morphology in the region sampled;
5. whether identification of minimally identifiable specimens to grosser taxonomic levels is deemed to be a useful part of one's overall analytical strategy;
6. whether identifications of minimally identifiable specimens to body region is deemed to be a useful part of one's overall analytical strategy;
7. the amount of time and other essential resources one has for analyzing the assemblage.

The next sections examine each of these determinants of identifiability in more detail. I will refer to examples from my own experiences because I have a better grasp of the underlying issues and decisions relevant to this discussion.

9.1.1.1 Analysts' Abilities

Researchers' abilities to identify fragmentary specimens vary. White (1992) notes that inter-analyst differences in what is considered identifiable are a concern when comparing assemblages. The longer one works with the same range of species, the more likely one is to become more knowledgeable. All other factors being equal, sites analyzed earlier in one's career are likely to have proportionately more non-identifiable or minimally identifiable materials than sites analyzed later, at least at the level of element identification. However, Driver (2011) observed a countervailing tendency, especially at the taxonomic attributions, toward what could be called "over-specific identification." He notes this is many times more characteristic of new students in the field, an observation I would support, but Gobalet's (2001) study (see below) indicates it may be more pervasive.

To give an example of experience-based increments in osteological and taxonomic identifications, I can look back at the effects of 20 years of practice in my career. In 1970–1971, I was a graduate student at the University of California, Berkeley and joined a team of relatively unskilled student sorters of the 165,000 bone specimens from Prolonged Drift. A skilled zooarchaeological supervisor was lacking because such individuals were then very rare, but one team member had paleontological experience, and I had studied human osteology. Our goal was to sort the very large assemblage into potentially identifiable, individually bagged specimens, and to place the less identifiable and completely nonidentifiable specimens into bag lots, weighing and counting as we went. In 1974, I went on to analyze several thousand potentially identifiable specimens isolated in the earlier sorts at the National Museum of Kenya, Nairobi, my first experience using comparative specimens to identify an East African archaeofauna. Through the late 1970s and 1980s, I analyzed about 30 more such African archaeofaunas.

In 1990, while working in the Kenya National Museum collections again, I decided to review the Prolonged Drift specimens that I had in 1974 put into a carton labeled the "Saint Jude Box," after the Catholic patron saint of hopeless cases. These were specimens with distinctive landmarks that I nonetheless had been unable to identify to element or taxon. I cleared the box completely in 2 days, identifying fragmentary bovid and equid metapodials, carpals, and tarsals to species and identifying all the "long bone shaft fragments" to elements. With these diaphyseal specimens, I could determine element, side, and taxon (species or Large Bovid, etc.) of about half of them without using comparative specimens, and I identified the balance to element and higher taxonomic levels (e.g. medium bovid) with the aid of the rich reference collections at the Museum. Going through these specimens, I reflected on my gains in knowledge of the morphology of East African ruminant and equid bones over those intervening 16 years.

When an analyst shifts regions and taxa, such benefits of long experience are largely lost. My ability to distinguish like-sized African bovids did not offer much traction when, in the late 1990s, I shifted to working with closely related members of the Otariidae, or eared seals. The only thing that I believe carried over was having "learned how to learn" minor differences in morphology: where to look (bone form, joint surface shape, muscle attachments) and why (feeding and locomotor anatomy).

Given these factors, most zooarchaeologists would probably agree that different analysts working with the same assemblage would probably sort identifiable to nonidentifiable bone differently. The question is, by how much? This was not, to my knowledge, tested with mammal taxonomic identifications until recently, although ichthyologist Kenneth Gobalet (2001) undertook blind tests with zooarchaeological fish identifications. Gobalet's results were less than assuring, with five fish analysts identifying between four and 18 species from the same samples and varying considerably in rates at which were assigned to family or higher taxonomic grouping (Gobalet 2001: Table 2). He notes there were more problems of over-specific, erroneous identifications than with the opposite, opining that it might be natural for someone trained on species in one area to attribute the same species to roughly similar from another region.

Morin et al. (2017a) experimentally assessed inter-analyst concordance, mainly focusing on mammal skeletal element identification and a restricted range of taxa, using 506 elements, allocated in about equal proportions to be the "input" to two separate fragmentation processes: marrow extraction (5354 specimens ≥1 cm) and bone grease production (10,522 specimens ≥1 cm), respectively. Red deer (*Cervus elaphus*) specimens dominated each sample, with over 500 complete skeletal elements of the 506. Each specimen ≥1 cm was assigned a random number linking it to its original element and species identification. Test volunteers had moderate to significant experience with identification of animal remains, including the species in the sample and were given an instruction guide that requested estimates of commonly used quantitative measures (Chap. 10). Details of the analysis of inter-analyst results are to be found in Morin et al. (2016:902–910). Two aspects of inter-analyst agreement were examined: percentage of specimens identified to skeletal element and error rates of these identifications. A high level of inter-analyst concordance characterized the element identification percentages with the bone marrow sample, whereas the bone grease sample was more highly variable, as might be expected, given the comminution of the assemblage and variations in experience among analysts. Error rates were compared, and these were more variable, in terms of *how* analysts erred, and some differences were statistically significant. Breaking this down by categories of elements, Morin et al. (2016:908–910) noted that, for given types of elements, inter-analyst error rates differed by less than 10%. Accuracy varied with which zone of the skeleton was analyzed. Long bones, especially shaft fragments, represented the least accurately identified class of elements, a topic that will be taken up in Chaps.10 and 18.

The Morin et al. experiment demonstrates that identification accuracy can be affected by involving sorters with different skill levels. With large assemblages, I routinely assigned the most experienced graduate students to make definitive element and taxonomic identifications, with ongoing spot-checks by me. However, experts can only work with what less skilled sorters select out as potentially identifiable and pass on to them. In my Santa Cruz lab, each grad student usually worked with a few undergraduate interns whom they tasked with preliminary sorts of a specific type (e.g. fish bone vs. lagomorph bone vs. bird bone). This allowed one-to-one feedback between the more and less expert members of any given team, as well as opportunities for the undergrads to acquire specialized skills.

When I worked in a field lab on the Gol Kopjes Site (SAES coordinate site number HcJe1) on the Serengeti Plains, Tanzania in 1983, a National Science Foundation funded field project headed by the late John Bower (Bower and Chadderdon 1986), a five-person lab team sorted over 50,000 specimens in about six weeks. I was fortunate to have as initial sort supervisor Kathlyn Stewart (Canadian Museum of Nature), then a doctoral student with fine zooarchaeological skills in identifying North American mammals and fishes. Several Tanzanian novice assistants had good natural abilities and high motivation. Stewart provided enough training and supervision to the primary sorters that, when I later made spot-checks of the “nonidentifiable” bone fraction they had sorted, I could not find any potentially identifiable specimens (unlike, I regret to say, the Prolonged Drift “nonidentifiable” fraction). This reassurance freed me to focus on the most identifiable assemblage component for several weeks in the field lab with the assurance that we’d overlooked very little. These anecdotes illustrate that the standards of a given analysis are only as strong as its weakest links, but that, with guidance and oversight, preliminary sorting by novices can produce acceptable results.

At home in my own laboratory, I used a “production chain” approach. Novices who had done well in my vertebrate osteology lab course made preliminary sorts under my own or my graduate students’ supervision. Grads made taxonomic identifications for taxa with which they were very familiar and recorded bone surface modifications. I worked at the end of the chain for taxa I know best, definitively identifying terrestrial carnivores and pinnipeds, while initially spot-checking everyone’s work. I checked grads’ ascriptions until I could not find errors. A team leader stopping to check a proportion of identifications by somewhat less skilled sorters does slow the rate of progress, but it makes the output more consistent. I could sometimes say that the buck literally stopped at my workstation before being entered in the database.

While analyzing her doctoral dissertation materials, Laura Scheiber (Indiana University), took an alternative approach to using skills levels of students. To analyze the predominantly bison specimens from the Donovan Site (Scheiber and Reher 2007), she organized teams of undergraduates who had completed my comparative osteology class, each team specializing in specific body segments: a cranium/mandible team, a vertebrae team, one team working with scapula and innominate fragments (because of possible conflation of these in preliminary sorts), fore limb and hind limb teams, and a team dealing with rare other species. Within a few weeks, the five bison teams had developed an excellent familiarity with "their" body segments, as well as a camaraderie that helped move the analysis forward. Team members checked one other's work and further reduced errors by flagging specimens that needed Scheiber's expert opinion.

9.1.1.2 Degree of Element Fragmentation

The extent to which osteological elements have been fragmented influences the ratio of identifiable to unidentifiable specimens in an assemblage. The more fragmented an assemblage, the less likely it is that all small pieces can be assigned to taxon, or even to element, as indicated by the Morin et al. study described above. Larger fragments of an element are more likely to have distinctive anatomical features than are smaller fragments of the same element. These differences can complicate comparing estimates of relative abundances from one site to another. However, such differences in intensity of fragmentation can be a rich source of information on human subsistence behavior.

From a half-century of ethnoarchaeological research, we know that the same forager group can produce variable proportions of identifiable to unidentifiable fragments at different locales and times of the year, according to their goals in handling carcasses. Binford's (1978, 1981) ethnoarchaeological case studies among the Nunamiut people of Anaktuvuk Pass, Alaska showed this well. At the caribou mass kill and butchery locale of Anavik, quite a few bones were discarded nearly whole after meat was stripped from them. Some long bones were discarded after being broken to extract marrow, overall resulting in few unidentifiable specimens at Anavik. By contrast, at Anaktuvuk, the village where families of the same group over-wintered, women manufactured bone grease by smashing up stockpiled caribou bones into small pieces and simmering them (Binford 1978), this produced many very small bone fragments which, had one not seen the bones entering the process, would have been difficult to identify to body region.

Both Anavik and Anaktuvuk incorporated mainly one species, caribou, so the proportions of identifiable to unidentifiable specimens in the two sites might not affect estimates of taxonomic composition. However, if the compositions of species processed at the kill-butchery versus residential sites were to differ from one

Fig. 9.1 Longitudinal section of a cow (*Bos taurus*) humerus, showing internal features of the diaphysis that aid in identification. Specimen from a dairy herd in Swarzedz, western Poland. Long bone specimens were donated to author by Professor Arkadiucz Marciniak, University of Poznan. Sectioning courtesy Richard Baldwin, University of California, Santa Cruz. (Photo by author)

another, then the divergent fragmentation intensities could pose problems for comparing taxonomic composition. The more fragmented state of one species could conceivably "conceal" it in the sample.

Identifying fragmentary long bone diaphyses, I have found that longitudinally sectioned long bones of species common in archaeofaunas with which I work, such as deer for my California analyses, and cattle for my East African research, facilitate identifications (Fig. 9.1). The sections permit matching diagnostic features of the medullary cavity wall with analogous ones on a fragment that lack distinctive features on their outer walls.

9.1.1.3 Recovery Techniques

Screen size and general recovery methods have been discussed Chap. 8 in terms of their influence on taxonomic representation, and they can also influence the proportion of identifiable to nonidentifiable bones. Very fine mesh or flotation may recover very small bits of the elements of larger animals, thus increasing specimen counts in the minimally identifiable and nonidentifiable assemblage categories. We saw this in my lab with the flotation samples that yielded the many very small fish elements identified by Dr. Boone: mixed in with these largely complete specimens were tiny "bone crumbs" of cancellous tissue from much larger mammals. If one wishes to compare ratios of identifiable specimens between or among sites, or relative abundances of very small to large animal species, one should begin with comparing sample recovery methods.

9.1.1.4 Levels of Taxonomic Identifiability

Another problem with identifiability has also been alluded to above. This occurs when more than one species of overall similar morphology and morphology might exist in an archaeofaunal sample. If the only medium-large sized artiodactyl ever documented in a region is the mule deer (*Odocoileus hemionus*), and if a specimen actually had no morphological traits distinctive of *Odocoileus*, some analysts would feel reasonably secure in assigning even fragmentary artiodactyl specimens in the mule deer size range, to that species.

Klein and Cruz-Uribe (1984:17–20) discuss the assumptions underlying taxonomic ascriptions in such situations, noting that analysts rely on their background knowledge of the species expected to occur in a given temporal and geographical context. In Africa, where many wild bovid species and three domestic species of the family Bovidae can coexist, zooarchaeologists and paleontologists routinely diagnose species on the basis of teeth, horn cores, and less fragmentary postcranial remains (e.g. Peters 1986a, 1986b). They place more fragmentary and taxonomically ambiguous bovid specimens into standardized size classes (Brain 1981; Klein 1976), for example, "medium bovid."

Zooarchaeologists working with central coastal California archaeofaunas face such issues, as both mule deer and pronghorn are historically or archaeologically attested. These two species are not even members of the same zoological family; mule deer are in the Cervidae, and pronghorns are in the Antilocapridae. However, they are of similar body size, and a very fragmentary specimen may not be taxonomically distinguishable. In this case, a wise zooarchaeologist would refer it to some more general classification, for example, "medium ruminant (or artiodactyl)."[1]

Driver (2011) cogently argued against such "identification by association," stating that each specimen should be identified based upon its own traits, rather than its likelihood of being derived by a species identified from other specimens. Discussions of Driver's point by Butler (2011) and Lyman (2011) are of interest. Butler (2011: 31) contended that Driver's recommendation against taxonomic "identification by association" can be modified under some circumstances. She points out that only one member of the family Catostomidae (suckers), *Catostomus macrocheilus*, the largescale sucker, is represented among identifiable specimens in some fish archaeofaunas with which she has worked. She argues that, based upon a thorough analysis of an assemblage, she is willing to assign less identifiable catostomid specimens to this species.

Lyman (2011) argued that zooarchaeologists would benefit from following paleontological practices in describing species, which involve detailed descriptions with

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[1] I prefer "Ruminant" because it reflects a more precise level of identification. The zoological suborder Ruminantia is one of three suborders within the order Artiodactyla, the other two being Suiformes (including pigs) and Tylopoda (including modern Asian camels and South American camelids). The Ruminantia includes all even-toed hoofed animals with ruminating stomachs, which genomic analysis shows to be a longstanding divergence in the order (Fernández and Vrba 2005). When referring to members of two zoological families within the suborder, as the Cervidae and Antilocapridae, Ruminantia or "ruminant" is more precise than is the name of the order.

illustrations of diagnostic features as well as blind tests of taxonomic identifications. This is excellent advice for rigorously describing archaeofaunal evidence for rare or first occurrences of a taxon in a region. However, zooarchaeologists have not yet worked through challenges of executing this protocol with archaeofaunal materials:

1. how we deal with differences in collection size;
2. how we define commonly encountered species not needing such treatment (Butler and Lyman 1996);
3. how we publish previously unpublished diagnostic postcranial elements that have not been addressed in paleontological works.

One method for advancing common zooarchaeological knowledge, along these lines as exemplified by paleontologically or zoologically trained researchers such as Guilday, Lawrence, and Peters (Chap. 4), is alternating between publishing on archaeofaunas and publishing identification guides to closely related species encountered in the archaeofaunas.

I counsel my students to take Driver's advice and be conservative in their taxonomic attributions, referring specimens to a more general, but solidly defensible, level of identification. This advice may seem to contradict the experience I recounted with the "St. Jude Box" in Nairobi. However, most of the mysteries there were resolved by identifying the *osteological element*, and then assessing whether enough other, species-specific osteological features existed on individual specimens to make a more definite *taxonomic* ascription than "large bovid," "small bovid," etc.

Practically speaking, when working with central coastal Californian archaeofaunas, I have maintained the separation between *Odocoileus* and medium ruminants in archaeofaunal report main table, even when no *Antilocapra* specimens had been found by evaluating specimens with comparative materials of both taxa. However, I have also noted in methods sections that, when no *Antilocapra* were identified among the most identifiable specimens, it is highly likely that the medium ruminant component in the sample were from *Odocoileus.* Moreover, for some types of analysis, such as processing effects, I combine these two categories, again noting that I am doing so and why.

Analysts working with Holocene archaeofaunas may begin by consulting reports on previously excavated sites of similar age and contexts, augmented by historical accounts and guides to modern regional faunas. However, as zooarchaeologists' reports have shown, even in the Holocene, the species we expect from historical records may not tell the whole story, as some species previously inhabiting a region disappeared before European colonization and record-keeping (Hildebrandt 1984; Lyman 1983). For those working with very old archaeological sites from Pleistocene or even Pliocene epochs, zooarchaeologists refer to species lists from previously analyzed paleontological and archaeofaunal assemblages of similar age and geographic context to assess the likelihood of encountering certain ancient species in their samples.

Assigning fragmentary specimens to species is further complicated by sexual dimorphism as well as by intraspecific geographic and temporal size variation.

For example, the closely related eared seal species of the north Pacific are so sexually dimorphic that females of the largest species, the Steller sea lion (*Eumetopias jubatus*) overlap in size with males the smaller California sea lion (*Zalophus californianus*) and large male northern fur seals (*Callorhinus ursinus*), all of which have been known to breed or haul out on the same isolated stretches of coastline or islands in historic or pre-European contact times. Analysts must be aware of such potential problems in their species samples, and of the need to use comparative specimens to resolve ambiguous cases.

Geographical differences in body size are known for regional populations of a single species. Analysts should be alert to the possibility that comparative specimens collected from regions other than those from which their archaeofaunal samples derive may differ in modal size, as Zeder (2005) showed was the case for *Capra aegagrus*, the ancestor of domestic goats. Early Holocene bison in North America display larger modal body size than historically documented populations (Lyman 2004; Wilson 1978), as is also noted for bear (Wolverton and Lyman 1998). Factors underlying such diachronic size changes are similar to those conditioning synchronic geographic variability in size: variations in the quality of forage and other essential resources, as well as interspecific relationships. All these factors call for considerable circumspection on the part of analysts making identifications of older archaeofaunas using modern comparative collections.

In sum, depending on the vertebrate species richness in a region and the intensity of fragmentation of a sample, the most prudent identifications of fragmentary specimens may be at higher levels of classification (e.g. genus, family, suborder) than the species level. Such taxonomic “demotions” will result in species abundance statistics to be based on fewer species-diagnostic specimens. These levels of identifiability nonetheless can work well for grosser assessments of taxonomic abundance, such as comparisons of ruminants vs. pinnipeds in regional archaeofaunas, and they certainly are functionally appropriate for studying butchery and processing activities, as will be discussed in the next section.

9.1.1.5 Uses of Less Taxonomically Identifiable Elements

Although they are of limited use in addressing research questions concerning regional paleoenvironment and species dynamics, less taxonomically and osteologically identifiable specimens can be used to investigate carcass handling (Table 9.1). Because humans will likely follow similar processing strategies with anatomically similar species, less identifiable specimens can be aggregated with species-identifiable ones to enlarge the sample size for studying butchery and culinary processing. Even in cases where the presence of two or more very similar taxa prevents definitive species identification, aggregating all specimens attributable to the same size class produces useful datasets. With these, I explored whether people at the Prolonged Drift site handled different-sized prey in a divergent manner, comparing element frequencies, locations and rates of cut marks, and other damage in this aggregate to a similar aggregate of larger bovid specimens (Gifford et al. 1980).

Marshall (1990) followed a similar strategy when comparing the handling of sheep and goats (which in fragmentary states, generally could not be differentiated) with handling of cattle at the central Kenyan pastoralist site of Ngamuriak.

Size-grouping specimens identified to varied taxonomic specificity is especially useful when certain body segments are consistently less likely to be species-identifiable. Vertebrae, for example, are relatively fragile (Kreutzer 1992; Lyman 1984, 1992). They are also likely to be broken down during primary and secondary butchery and in culinary processing by boiling (O'Connell et al. 1990; Oliver 1993; Yellen 1977). Their fragmentation renders vertebrae less likely to be assigned to genus or species than are more durable carpal and tarsal bones. To obtain a comprehensive view of carcass processing strategies, including transport decisions, one's sample must include less taxonomically identifiable specimens along with those that have been identified to genus or species.

However, lumping similarly sized taxa is less useful for other research questions. Putting all wild specimens in a single pool would not be productive for investigating hunting. Closely related wild species have divergent ecological niches and behaviors, hunting tactics for each may vary, and pooling might obscure these. Likewise, the processing of domestic versus wild animals of similar sizes may differ, and grouping these together will obscure this.

9.1.1.6 Uses of Less Osteologically Identifiable Elements

As with specimens of varying levels of taxonomic identifiability, it may be worthwhile to place minimally identifiable elements into general body region categories and use them for taphonomic and butchery analyses. These specimens are often the same fragile or heavily processed elements that cannot be identified to species. Fragments of crania, vertebrae, ribs, and long bone diaphyses can be assigned to "minimally identifiable" categories. As noted regarding taxonomic identification, the decision whether to use minimally identifiable element categories stems in part from the research questions zooarchaeological practitioners want to ask. If one is mainly interested in what taxonomic abundances can reveal about changes in climate, ecology, or species over time, these specimens are not useful. However, if one is interested in teasing out information on human handling of animals or the archaeofauna's taphonomic history, they merit attention (Ziegler 1973).

This sometimes reveals the presence of body segments that may be underrepresented by better-preserved specimens. Ethnoarchaeological research has highlighted that hunters handle limbs of large prey differently than axial elements, especially vertebrae, when transporting larger mammals' body segments (Chap. 19). These findings and those on differing carnivore impacts on various body segments (Chap. 12) make it critical to assess the presence or absence of vertebrae in archaeofaunas. Here, the minimally identifiable component can shed important light on whether, for example, vertebral segments are present, albeit in fragmentary form, in an assemblage.

In my East African research, I analyzed archaeofaunal samples from Ele Bor A, a stratified rock shelter site near the Kenya-Ethiopia border (Phillipson 1984; Gifford-Gonzalez 2003), which demonstrated the survival of vertebral fragments, even in a highly comminuted archaeofauna. The modal maximum dimension of specimens from the site was 2 cm, with very few pieces greater than 5 cm. In one stratigraphic unit, 57% of 1404 taxonomically identifiable bovid specimens were isolated teeth, carpals, tarsals, sesamoids, first and second phalanges, all relatively dense elements that typically withstand attritional processes. However, cervical vertebrae accounted for 7% of bovid specimens. In another layer with 978 bovid specimens, cervical vertebrae comprised 4% of bovid specimens, ranking immediately below teeth, carpals, tarsals, and sesamoids in frequency. Dense segments of fragile vertebral elements can survive even in assemblages subject to heavy attrition, and testify to transport of these body segments to the site. This illustrates the risks of assuming certain body segments were not transported, simply because they do not fall into the most osteologically and taxonomically identifiable categories (Table 9.1).

Careful study and enumeration of minimally identifiable or nonidentifiable specimens can directly shed light on the economics of animal processing. Outram (2001, 2003; Outram and Mulville 2005) made the case for study of nonidentifiable specimens to assess rates of bone grease extraction, a labor-intensive activity, which in turn reflects a strong motivation on the part of the processors to recover fat. Working with archaeofaunas from the Neolithic Anatolian site of Çatalhöyük, Martin and Russell (Martin 2001; Russell and Martin 2005), were able to use the ratios of nonidentifiable specimens as one of several indices to determine whether samples derived from feasting or everyday animal processing, which at certain seasons included bone grease production. This topic will be taken up in more detail in Chap. 15.

9.1.1.7 Identifiability Decisions Based on Logistical Constraints

The proportions of identifiable to nonidentifiable specimens in an assemblage also may depend upon the amount of time and essential resources an analyst has at their disposal. I can give an example from my own research. In 1983, when I worked as zooarchaeologist on the Gol Kopjes excavation project in the Serengeti National Park, the Tanzanian economy was at a very low ebb. Gasoline was in severely rationed, and supplies of all sorts were hard to find. The Tanzanian government was also discouraging temporary exportation of archaeological samples to neighboring Kenya for a more detailed analysis in the Kenya National Museum, despite lacking comparable collections in Tanzania. As a result, I needed to sort and identify nearly all recovered specimens in a lab at the Serengeti Wildlife Research Institute (SWRI) at Seronera, using supplies at hand and comparative specimens of the most common bovids in the Park, plus whatever we could collect within walking distance of SWRI. A further complication was that SWRI's electricity was cut, and we had the

12-hour equatorial day for work. We were in the lab an hour after first light and stayed until dusk. As noted in earlier, a fine crew of sorters isolated thousands of potentially identifiable bones in six weeks.

I arrived 2 weeks into the excavation, with 4 weeks to do the work and the chance to export only a few hundred specimens to Kenya for further examination. Bones from deeper levels of the main, Gol Kopjes site were often covered with calcium carbonate concretions. This did not hinder element or taxon identification but did obscure surface modifications. We quickly exhausted our supply of dilute acetic acid for removing concretions from specimens, and no more could be obtained.

Given these limitations, I decided to depart significantly from my usual analytic tactics. Previous radiocarbon dates and ceramic evidence indicated the Gol Kopjes cultural sequence spanned about 4000 years, encompassing the time when pastoralism appeared in East Africa, and the excavator wanted to monitor these developments in the Serengeti. This could be assessed by the presence or absence of domestic fauna in successive levels. I decided to process as many highly diagnostic (more complete) specimens as possible in the time allotted. I opted not to spend time further identifying minimally identifiable fragments but instead to focus on taxonomically diagnostic elements: teeth, carpals, tarsals, long bone joint surfaces, and bovid anterior cervical vertebrae, which are often species-diagnostic.

These choices affected the categories of identifiability into which bones were placed. Although I had satisfied myself that the “nonidentifiable” category did not contain potentially identifiable elements, I believe that the general taxonomic categories (e.g. small bovid, medium bovid) and minimally osteologically identifiable body segment categories in the Gol Kopjes archaeofauna are proportionately larger than they would have been, if I had worked with them for a longer time with good comparative specimens – in which case, a good percentage of these would have been “promoted” to a species identification. This is a stark example of the influence of time and resource limitations on proportionate levels of identifiability and recording of other distinctive traces. I believe that significant and reliable information was gathered from the elements we processed. Nonetheless, I recognize that the analytical “triage” created a different database than those generated by my analyses in more leisurely, better-equipped contexts.

Zooarchaeologists who work with in foreign countries from which collections cannot be exported may look with undue envy at colleagues who work with collections in their home countries, imagining the luxury of being able to check identifications over months or even years. In reality, many zooarchaeologists working on home country archaeofaunas also face deadlines for project funding and reporting, permit and resource crunches, coping with some of the same problems as overseas workers. In some situations, analysts can’t do much about the root causes of logistical problems that force them to streamline their analyses in ways they’d rather not. The important step is to be as specific as they can about the corners they had to cut in the strategy they in fact did follow as the best way to meet their project’s goals.

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Chapter 10
Zooarchaeology's Basic Counting Units

Zooarchaeologists work with the circumstantial evidence of human behavior found in faunal specimens and their contexts, seeking to understand the human decisions that produced that evidence. They aim to elucidate changes in humans' animal use over time and how these may relate to social, ecological, or evolutionary processes. When moving from analyzing a single sample to comparing multiple assemblages, one confronts the question of how to compare these reliably. Such comparisons are usually made using quantitative measures of abundance. Whenever one describes patterning in faunal assemblages, one is counting individual elements or variables recorded from them. All the evolutionary, environmental, and biogeographical inferences drawn from archaeofaunas, all the behavioral and cultural inferences, and all the comparisons among archaeofaunas that construct narratives of change over time or space depend upon frequencies and relative abundances of different animal remains and of the species they represent. When Binford (1981, 1984) argued that frequencies of elements with different nutritional values could show whether a site was a kill/butchery locale or residential camp, this called for counting the elements and estimating their relative frequencies. When Klein (1982) asserted that certain animals were hunted and others scavenged, his inferences were based upon the shapes of mortality profiles derived from the relative frequencies of teeth in different age categories.

Counting bones and teeth may appear a straightforward matter. At the simplest level, one simply sorts different element types, identifies the species, and totals the specimens from each different element and species. However, three traits of vertebrate specimens require additional reflection and care:

1. Vertebrate skeletons vary in the number of elements they contain, according to species.
2. Vertebrate skeletons vary in the size and durability of their skeletal elements, according to taxon, age, and size.

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3. Human processing for food and raw materials, as well as taphonomic effects after discard, differentially affect fragmentation of vertebrate element. Moreover, the intensity of each such effect can vary from case to case.

Chapter 9 noted that zooarchaeologists do not all use identical tactics and standards when working with specimens that differ in their degrees of identifiability. Likewise, not every analyst counts specimens identically, and debate continues over the best methods for determining and comparing species abundances. However, some standardization has emerged, despite debate about details, and this is worth introducing before moving on to distinctive signatures of various actors. Chapter 18 will delve more deeply into the use of zooarchaeological counting units in various statistical tests. Chapters 19, 20, and 21 discuss ongoing debates over their respective applications and limitations.

Some literacy in the problems of quantifying archaeofaunas is important because studies have shown that "significant" patterns in faunal data can be produced by the counting methods themselves rather than by intrinsic patterning in the faunal assemblage itself (Chap. 18). It really comes down to what one wants to spend one's time explaining: patterns robustly present in the assemblage one studies, or artifacts of one's counting and comparative methods.

10.1 Basic Zooarchaeological Counting Units: NISP, NSP, MNE, MNI, MAU

This section examines the fundamental counting units in zooarchaeology: how they are derived, and the practical and theoretical problems they involve. Lyman (1994a) made a comprehensive, critical review of the many terms and units of quantitative measure that appear in the zooarchaeological literature (see also Lyman 2008). Some of his trenchant observations will be repeated here and in Chap. 18. In that paper, Lyman noted that units of measure and their applications have changed since the 1960s. He attributes much of this to a growing recognition of the role of taphonomic processes in producing the assemblages with which zooarchaeologists work. The earlier assumption that taxonomic abundances in archaeofaunas directly reflect ancient environments or human behavior has been replaced by the understanding that taphonomic processes, including human impacts, affect archaeofaunal samples. Types of measure that permit exploration of taphonomic processes, including human effects, emerged.

While Lyman (1994a, b: Table 1) found some 122 units of measure in the zooarchaeological and paleontological literature, this chapter introduces those most commonly used over the last 30 years:

1. Number of Identified Specimens (NISP)
2. Number of Specimens (NSP)
3. Minimum Number of Individuals (MNI)
4. Minimum Number of Elements (MNE)
5. Minimum Animal Units (MAU)

10.1.1 NISP (Number of Identifiable Specimens)

The NISP statistic is the total count of specimens that are *taxonomically* identifiable, commonly to the species or the genus level. Recall that a "specimen" here is an actual archaeological object as recovered and studied, which may be either a whole element or, more commonly in archaeofaunas, part of an element. NISP may incorporate as "identifiable" those pieces that must be referred to higher levels of taxonomic identifiability, as outlined in Chap. 9, for example, "medium ruminant." Thus, in an assemblage of 300 specimens with 78 that can be identified as turkey and 22 as deer, the NISP for turkey is 78 and that for deer it is 22.

NISP and NSP (see below) both fall into what Lyman (1994a) distinguished as observational units, that is, they quantify directly observable objects. There are either 17 bone specimens in the level bag dumped on the lab bench or there are not, and you can count them twice to make sure. Some zooarchaeologists may include somewhat identifiable specimens, which I called minimally identifiable in Chap. 9, in NISP counts – specimens that can be assigned to some taxonomic level and size group, for example, "very large avian." NISP by definition excludes nonidentifiable (NID) specimens. The statistic thus does not encompass all the specimens in an assemblage, and, depending upon the degree of fragmentation of the skeletal elements, NISP can represent a small fraction of the total assemblage of bone and tooth specimens.

10.1.2 NSP (Number of Specimens)

Wolverton (2002) introduced the term NSP (Number of Specimens) to refer to the total count of pieces of all levels of identifiability in a sample. Archaeologists only recently began to discuss the minimally identifiable (what I have abbreviated to MID) and nonidentifiable (NID) components of archaeofaunal assemblages. This may reflect a shift in zooarchaeologists' foci from predominantly on climate change and gross patterns of prey acquisition to finer-grained analyses of carcass processing behaviors (e.g. Outram 2001). Chapter 9 made the case for a closer study of less-identifiable specimens, because they may reflect various handling tactics, such as fat-extraction and other forms of intensive culinary processing (Chap. 15). Wolverton (2002) discussed analysis of fragmentation rates in faunal assemblages as part of a carcass-focused approach. He argued that the degree of fragmentation could be more closely specified by using a ratio of the total Number of Specimens, or NSP (the sum of all identifiable, minimally identifiable, and nonidentifiable specimens) to NISP than does using either or MNE:NISP or MNI:NISP. Fragmentation indices will be discussed again in Chap. 21, but the takeaway message of this chapter should include the value of minimally identifiable and nonidentifiable materials in archaeofaunal samples. The next sections review common quantitative measures based on NISP.

10.1.3 Minimum Number of Individuals (MNI)

The Minimum Numbers of Individuals is an estimate, based on NISP, of the lowest number of individual animals necessary to have provided the single most abundant element of each taxon in a sample. Paleontologists used the MNI since the 1920s. Theodore White, trained as a biologist and paleontologist, popularized the method in archaeological circles in the 1950s. In a series of articles in *American Antiquity* White (1952, 1953, 1954, 1955) published his analyses of upper Midwestern archaeofaunas, using MNI to quantify his results. Lyman (2008:41–42) notes that White did not use this statistic to estimate relative species abundances, as many zooarchaeologists did later, but rather derived meat yield estimates for hunted animals from MNI.

MNI is derived by finding the most abundant element for each taxon. If, among 22 deer elements in a sample (deer NISP = 22), the unique element with the highest count is the left lower third molar, totaling three, then the sample's deer MNI = 3. A minimum of three individual deer would have had to contribute a left lower third molar to produce this count. More than three deer could be represented in the sample, but preservation and sampling gave the zooarchaeologist only three teeth of this one type, of which there is only one per animal. Thus, MNI does not directly reflect what one of my undergraduates once called "paleoreality." In practice, the most basic procedure for calculating MNI, as in the example of the deer molars, usually depends on counts of bilaterally symmetrical elements of a vertebrate body (that is, having paired left and right elements). In theory, a single element of the axial skeleton, for example, the 2nd cervical vertebra, or axis, could be the basis for a MNI estimate, though this is less common, given the differentially greater fragility of such skeletal elements.

NISP values in an assemblage are primary quantitative data, derived from a straightforward count of tangible specimens. MNI represents a secondary abstraction from the primary data. Given this, why use MNI at all? It can be useful because of biases introduced to NISP by intrinsic properties of vertebrate skeletons and by postmortem processes. These are:

1. Different vertebrate species have variable numbers of skeletal elements in their bodies (Fig. 10.1).
2. Human modifications may differentially affect specimen counts, as:
    (a) butchery and transport of body segments act disparately on vertebrate bodies of different sizes;
    (b) secondary processing inflicts disparate levels of breakage on elements of different species.
3. Nonhuman taphonomic processes can affect taxonomic representation through differential destruction of more delicate elements.
4. Collection biases (screen size, etc.) can differently affect representation of various species, as outlined in Chap. 8.

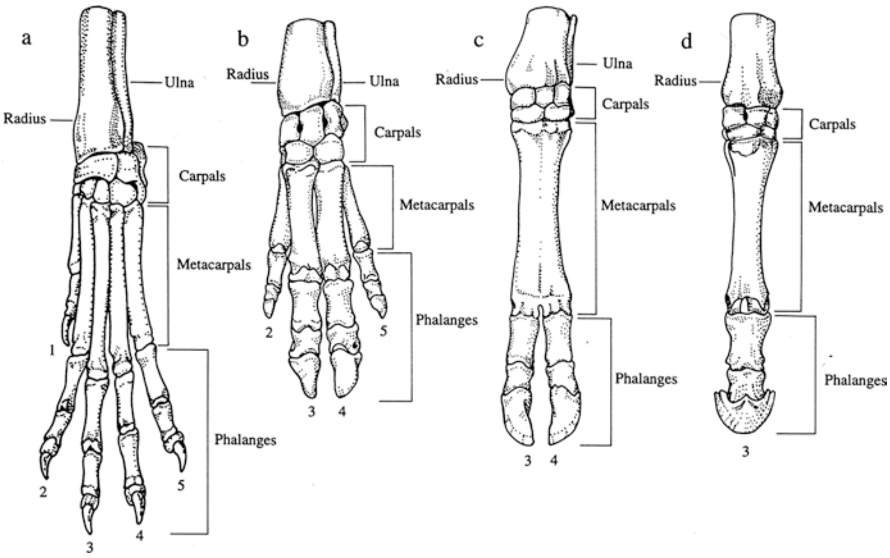


Fig. 10.1 Illustration of variable number of skeletal elements, solely within the Class Mammalia, using foot bones as an example. Feet not drawn to scale. From left to right: (**a**) wolf (26 elements); (**b**) pig (23 elements); (**c**) cow (12 elements); (**d**) horse (12 elements) (Source: Reitz and Wing (2008: 98, Fig. 3.14). Drawing by Virginia Carter Steadman, used with permission of senior author and Cambridge University Press.)

The MNI method corrects for biases created by variable numbers of bone elements in different taxa, and it may help cope with human and nonhuman taphonomic biases. Thus, MNI appears to offer analysts a solution to problems with NISP.

Lyman (1994a: 38–57) offers a detailed historic overview of the uses and permutations of MNI in zooarchaeology, and physical anthropologist White (1992) outlines the variability in deriving MNI statistic from the standpoint of his field. Most human osteologists normally compare each individual fragment of a given skeletal element, closely assessing whether right and left specimens could have come from the same individual on the basis of size, idiosyncratic morphological details, pathologies, or other traits. All specimens that cannot reasonably be attributed to the same individual are then counted as representing a separate "minimum individual" in reckoning the number of individuals contributing the specimens to a sample (White 1992).

Zooarchaeologists have not usually followed such painstaking reconstitution of individual body segments, a tremendous challenge in assemblages of thousands of specimens representing multiple species. Instead, most count right and left elements of a taxon. A few zooarchaeologists have taken an approach that parallels physical anthropologists' when attempting to "refit" individual carcasses from an archaeofaunal sample of a single species (e.g. Enloe and David 1992; Frison and Todd 1987; Waguespack 2002), as will be discussed in Chap. 25.

Further variations in deriving MNI exist in zooarchaeology. It is relatively common for zooarchaeologists to subdivide elements of one species into age groups, minimally with newborns, juveniles, and adults, and to calculate MNI for each. Zooarchaeologists dealing with stratified sites may calculate species MNI for the sample from each stratum that the excavator has defined as significantly distinctive. Some zooarchaeologists subdivide their samples into groups keyed to different functional zones within a site. For example, instead of estimating a total NISP and MNI for an entire settlement, many archaeologists would derive NISP and MNI for each house or house compound.

Given its efficacy in correcting for problems with NISP, one may wonder why MNI is not universally used as a measure of relative abundance in zooarchaeology. However, some complications exist with MNI as a quantitative measure. First, in contrast to NISP or NSP, MNI is, to use Lyman's (1994b) terminology, a *derived analytical unit*: it is a mathematical transformation of an observational unit, NISP. Justification for such a transformation is that it is thought to represent some property of a living system. In the case of MNI, the measure is an estimate of the minimum number of intact carcasses from which the observational units – the specimen counts – are necessarily derived. The same holds true for the MNE, or Minimum Number of Elements, statistic (see below). However, Grayson (1984a) noted that subdividing faunal assemblages as zooarchaeologists regularly do and then combining or comparing the MNI statistics from those subdivisions can complicate estimates of taxonomic abundances. This aspect of MNI will be taken up in detail in Chap. 18. For now, it is enough to understand that the use of MNI in zooarchaeology has its complications.

10.1.4 Minimum Number of Elements (MNE)

The Minimum Number of Elements statistic parallels the MNI, being an estimate of lowest number of individual *skeletal elements* of a taxon, for example, deer femurs, which had to have been present to produce the fragmentary femoral specimens in an assemblage. This statistic, like MNI, is derived from close examination of NISP. In fact, all MNI estimates are based on at least an informal reckoning of the Minimum Number of Elements, a point made by both Lyman (2008) and Marean et al. (2001), but, paradoxically, until quite late in zooarchaeology's development, just how researchers reckoned MNE was not much discussed in the zooarchaeological literature.

Marean et al. (2001) offered a critical assessment of various methods used in estimating MNE, as well as presenting their GIS-based method for estimating MNE. They characterize some such methods as *fractional*, because they tally the fraction of an element represented by specimens, while others are based on counting specimens with portions of an element that *overlap*. Fractional approaches include counts of osteological landmarks unique to a given element, such as the bicipital groove of a deer humerus or the third trochanter of an equid femur or an integer

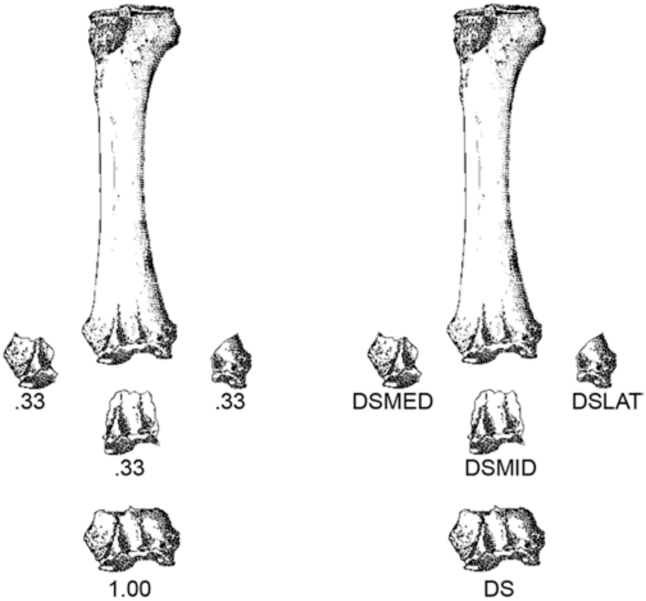


Fig. 10.2 *Left*. Klein and Cruz-Uribe's (1984) and *Right*. Gifford-Gonzalez's systems for quantifying element fragments to estimate MNE and MNI, using the distal radius as an example (Illustration by the author.)

representing the proportion of an element represented. A tabulation of left and right landmarks for all elements has the potential to include limb bone shafts, formerly excluded from many tallies (Marean et al. 2001).

Perhaps the best-described example of the fractional approach is that of Klein and Cruz-Uribe (1984). They developed a BASIC computer program for deriving MNI, which, Marean et al. (2001) stress, depends upon first estimating MNE. Their approach specifies the proportion of a proximal or distal long bone fragment represented, producing a kind of MNE estimate in the process. For example, for a distal radius, this assigns decimal estimates of the proportion of that fragment present (Klein and Cruz-Uribe 1984:108–10). Figure 10.2 illustrates their approach, aling with an approach I have used for many years. To derive MNI, they total the fractional values, effectively producing an MNE statistic.

Marean (personal communication, 2011) and colleagues developed a visual template system for recording bone portions, which can be used in Microsoft Access® or FileMaker® applications. Once one selects a specific taxon and element, with standard data field prompts, an image of the element is presented along with data fields for registering which zones of the element are present (Fig. 8.3). This offers the advantage of permitting persons with relatively little training to accurately record the portion of the element represented by a specimen. In the process, the visual system also portrays and notes major landmarks on each osteological element. The system uses these data in attached Excel® pivot tables to automatically reckon MNE and MNI using several common methods for estimating MNI. Cleghorn (personal communication, 2010), one of the developers, cautions that the pivot table function has been known to produce erroneous estimates, due to spontaneous changes in its settings, and should be monitored closely. However, this system, available from the developers, offers the advantage of swift derivation of MNI variants.

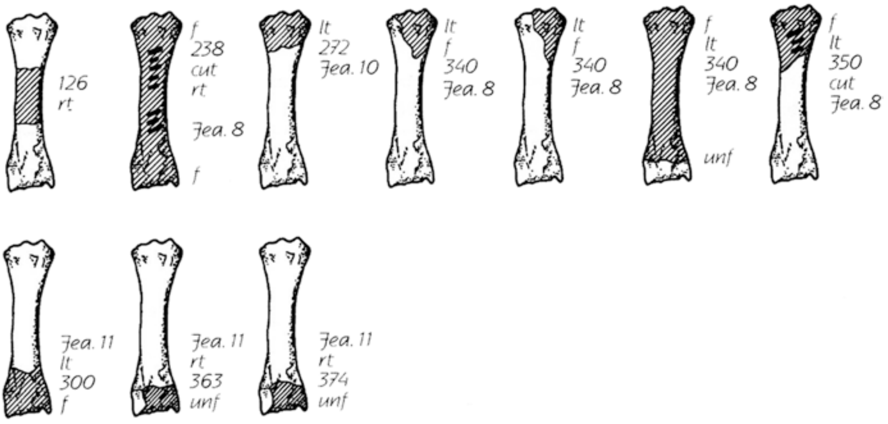
Lyman (1994b:53) argued that the Klein and Cruz-Uribe fractional integer system can underestimate MNE, as it does not take into account overlapping and hence mutually exclusive bone portions, nor does it consider redundant patterns of portion representation. For example, Marean et al. (2001) note only the most durable portions of elements were preserved in a heavily fragmented fauna from Lukenya Hill, Kenya. Consistent patterns of butchery and transport may also capture the same portions of many different animals' bones, as was the case with large wild bovids' distolateral radius fragments apparently chopped off the element and carried back with the meat at Prolonged Drift, Kenya (Gifford et al. 1980). If such fragments were tabulated using the fractional integer system, they would produce a lower MNE than actually represented by recording the osteological portion represented and counting each such specimen (Fig. 10.2). The "landmark" system of fractional notation would avoid this problem.

10.1.5 "Overlap" Methods

Marean et al. (2001) describe the second set of MNE estimation approaches, the "*overlap*" method, a time-honored approach recently used by a several researchers (Marean et al. 2001; Reitz and Wing 2008). This arises from the technique of laying out all right and left specimens of a skeletal element from a given taxon and checking for refits between pieces, or for anatomical overlaps among specimens of the same side, as these could not derive from the same element. A variant of this method copes with the common reality of limited space and time to lay out all specimens of the same element, especially with very large samples: one draws outlines of each identifiable specimen on standard templates of right and left elements for that taxon. Aggregates of these outlines are relatively straightforward to check for overlaps, thus serving as the basis for reckoning MNE. Figure 10.3 illustrates Reitz and Wing's version of this method. The MNE for radii would equal 5, for the five left-side proximal specimens represented in the sample. For ulnae, MNE = 4, based on the overlapping portions of the left side specimens.

When I began zooarchaeological analyses in the 1970s, database management was done with main-frame behemoths that required input by punch cards. Coding formats were restricted to the cards' 80 columns, were always linear, and of course lacked digital visualization capabilities. Over the years, the system I used for recording specimens evolved with technology, now being based on an inter-platform compatible FileMaker® application on a personal computer. However, after a few too-early experiments in digital visualization capabilities, I remained with non-

Hypothetical Collection: Radius



Hypothetical Collection: Ulna

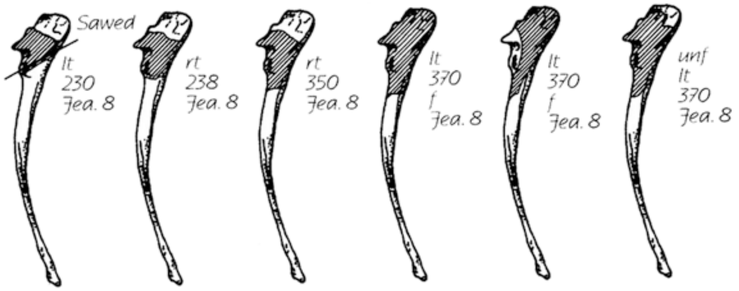


Fig. 10.3 Outlines used by Reitz and Wing (2008: Fig. 7.13) in their "Hypothetical Collection," to document the portions of deer radii and ulnae actually represented in the sample (dark shading). Visual representations of portions can then compared to estimate MNE. Notes include modifications and other primary traits of specimens. Key: *rt* right, *lt* left, *unf* unfused, *f* fused (Reproduced with permission of authors and Cambridge University Press.)

digital records for describing bone sections and placement of surface modifications. In a primitive attempt to emulate the "overlap" method with non-visual records for estimating MNE and MNI, I assigned to each recorded specimen a description from a very fine-grained list of "Portion" codes (Table 10.1) as shown in Fig. 10.2. The Portion field is based on an older, two-field approach to element representation developed by in the 1970s (Gifford and Crader 1977).

To produce MNE and MNI estimates, I digitally sorted each skeletal element of a given species according to side and the portion of the bone present. Then, using intuitive reasoning about possibly overlapping portion categories, I produced a MNE estimate – some might say a guesstimate – for each element. At this final step, all resemblances to real overlap approaches ended and there entered a truly subjec-

Table 10.1 Gifford-Gonzalez portion codes: a pull-down menu facilitates entry of short label for each specimen entered into the database

Short label	Long label
CO	Complete
PX	Proximal
PSH	Proximal + shaft
PXLAT	Proximolateral
PXMED	Proximomedial
PXFR	Proximal fragment
PXANT	Proximal anterior
PXPOS	Proximal posterior
SH	Shaft
SHANT	Shaft anterior
SHPOS	Shaft posterior
SHMED	Shaft medial
SHLAT	Shaft lateral
SHFR	Shaft fragment
MID	Middle
CYL	Cylinder (complete)
DS	Distal
DSH	Distal + shaft
DSLAT	Distolateral
DSMED	Distomedial
DSHF	Distal half
DSFR	Distal fragment
DSANT	Distal anterior
ANT	Anterior
ANTMID	Anterior + middle
ANTLAT	Anterolateral
ANTMED	Anteromedial
ANTFR	Anterior fragment
POS	Posterior
POSLAT	Posterolateral
POSMED	Posteromedial
POSMID	Posterior + middle
POSFR	Posterior fragment
SUP	Superior
INF	Inferior
LAT	Lateral
LATFR	Lateral fragment
MED	Medial
MEDFR	Medial fragment
HFAP	Half anteroposterior
HFL	Half longitudinal
END	Fused epiphysis indet.
FR	Fragment

Portions are used with bilateral symmetry to estimate specimen overlap in determining MNE and MNI. See text for discussion of pros and cons of this approach tive element that could vary among analysts, affecting replicability. Despite the fact that I have been using FileMaker® relational databases capable of incorporating visual data for over a decade, I did not move in that direction. However, Marean et al. (2001) did so, using a Microsoft Access® platform.

Marean et al. (2001) describe the formerly widespread method of drawing outlines of specimens on tracing paper laid over a "template" drawing of a complete element from the species. I have printed multiple paper copies of a template, with more than one specimen drawn on the same page, and then converted these to transparencies that could be superimposed for ease of comparison of a larger dataset. However, very large assemblages present challenges to such a manual approach, as described Marean et al. (2001). To cope with these, Marean et al. (2001) developed a version of the overlap method, using custom coding within ArcView® GIS software to search for overlapping versus non-overlapping diaphyseal fragments. This was intended to enable research on carnivore-modified long bones (see Chap. 12). Their method begins with an analyst tracing the outlines of long bone fragments on a digital pad or on paper and then scanning the tracings. Images for specified elements, sides, and taxonomic groups are automatically compiled by the computer program and compared for overlaps. This approach, though requiring both the appropriate software and expertise, as well as periodic updates of the software, offered the possibility of producing accurate estimates of overlaps and hence, reckoning MNE.

However, in an evaluation of the method, Lyman (2008:221–222) reports difficulties in replicating the same levels of accuracy with this package. These mainly stemmed from problems in consistently producing good manual tracings of fragmentary specimens. Some human error can be introduced at the image tracing stage, which might be improved by using high-end digital input scanning or geometric morphometric technologies and analysis. However, this kind of technology is nonetheless out of the reach of most zooarchaeologists.

After about 45 years of working with archaeofaunas and estimating MNE in various ways, both fractional and overlap, I am convinced that the osteological landmark system is most broadly suitable for estimating MNE, especially when time for analysis is relatively short. Butler developed a landmark system for use with fish remains to estimate MNE in the 1990s (V. Butler, personal communication, 2017). Landmark tabulation permits a swift reckoning of redundant element portions and is especially useful in permitting MNE estimates from long bone shaft fragments in mammals. Moreover, it does not require the laborious tracing of specimen shape and physical or mechanical superposition of these images to produce an acceptable estimate of skeletal element abundance. Reckoning element abundances using their most common left, right, or axial landmark can be used by consulting archaeologists, who may not have the luxury of months or even years of lab work to obtain such statistics. While the GIS-based approach is certainly appropriate to research involving taphonomic or human attritional effects, it requires more intensive investment of time than possible for many who nonetheless aspire to produce estimates of MNE.

One point to remember when applying any method for estimating MNE is that they are only as good as an analyst's ability to definitively determine the taxon and element of the bone specimen in the first place.

10.1.6 Minimum Animal Units: MAU

In *Nunamiut Ethnoarchaeology*, Lewis Binford (1978) introduced a statistic that he initially called "Minimum Number of Individuals." Later, in recognition of the divergent nature of his own statistic from the classic MNI, he renamed it "Minimum Animal Unit" (e.g. Binford 1984). Like MNI, Binford's MAU statistic is derived for skeletal element counts (NISP) and depends upon MNE. For bilaterally symmetrical specimens, MAU is the product of the total of all right and left, which are then "normed" by dividing by two (the number of times the element occurs in the skeleton). So, 15 right tibias and 35 lefts yields a MAU of 25: 15 + 35 = 50 ÷ 2 = 25. Binford treated axial body segments such as cervical vertebrae (minus the atlas and axis), thoracic, lumbar vertebrae, and ribs by totaling each type and then dividing by the number of those elements in a given taxon's body. Thus, a total of 50 caribou lumbar vertebrae, with five such elements in an individual, yields a MAU of 10: 50 ÷ 5 = 10.

Binford contended that MAU is a more realistic estimate of the proportion of body segments processed at a site because it shows "undistorted conversions of the actual count of bones into animal units" (Binford 1978:70). Grayson (1984a) points out that this statistic is really a normed specimen count and asks, if the analyst is interested in the specimens actually present in a sample as a unit of analysis, why not use the straight specimen counts? This would be NISP or MNE, depending on specimen completeness. Using the total of 50 caribou tibias would more closely approximate the number of segments in the sample than does the MAU figure.

In practice, Binford's derivation of the MAU statistic treats certain element classes differently than others, and his reasons for lumping certain elements and not others were never fully explained. Given that he was working from his experience of Nunamiut carcass utilization, it is possible that his decision related to units commonly handled by the butchers. Rib slabs comprising all the ribs from one side of the body plus thoracic vertebral units were common segments into which Nunamiut butchers subdivided, stored, and later used carcasses (Binford 1978). Other reasons may relate to factors discussed in Chap. 9, including varying levels of identification proficiency, time and resource considerations. Many zooarchaeologists, and I am one of them, cannot definitively identify individual thoracic vertebra or ribs without comparative specimens, except, perhaps, for the anterior- and posterior-most elements. In a field situation, the question arises whether it is worth the time and effort to reach this level of specificity, which may involve transporting specimens to another location. If one's analytic aims are served by coarser, lower-resolution osteological identifications, the choice is an acceptable tradeoff.

Another consideration in deriving MAU is that, like MNI, it depends upon a reasonable sense of MNE in the first place. As with MNI, persons using the MAU statistic have seldom explicitly outlined the steps involved in determining MNE. It is always possible, as it was reported in Binford's Nunamiut ethnoarchaeological research, that most specimens are close to complete, and reckoning MNE is not an issue. This is not the case, however, with most archaeological samples, which requires that analysts make their procedures for using more fragmentary specimens to determine MNE values explicit.

Despite the problems with MAU outlined here, Binford used a conversion of it, "%MAU," in a series of forceful arguments about early hominin hunting vs. scavenging. Deriving %MAU entailed dividing each element's MAU value in a sample by the highest MAU value in that sample and multiplying the result by 100 (Lyman 2008: 234–235). Binford's use of %MAU in his arguments led others, including some who wished to rebut him, to use it as well in their engagements with Binford's assertions. MAU thus became a common statistic for representing and comparing element frequencies among assemblages among paleoanthropological zooarchaeologists in the later 1980s and 1990s. It was less used among other analysts of archaeofaunas. Chapter 18 considers how MAU shares with MNI "aggregation effect" problems, and Chaps. 21 and 22 discuss applications of MAU to zooarchaeological issues.

10.2 The Relation of Counting Units to Research Questions

Few zooarchaeologists have clearly described how the quantitative means they use relate to goals of their research. Yet, as Lyman (1994b, 2008) has stressed, the nature of the research problems one opts to pursue and the kinds of data on which one chooses to focus, may require one or another set of quantitative units, and thereby, choice of appropriate statistical tests. Just as most of us would not select a crescent wrench to drive a nail into a wall, zooarchaeologists must know enough about the strengths and weaknesses of various units of measure to know the most suitable one for working through a specific problem. Whether one is making intrasite vs. intersite comparisons, working with stratified or non-stratified sites, studying changes in taxonomic abundance or butchery and processing behavior, whether the sample comprises species of disparate skeletal element counts, and other circumstances must all be considered in choosing the most appropriate unit of measure. Chapter 18 will go into greater detail on these issues, but a few examples here will support this assertion.

Klein‘s (e.g. 1984, 1986, 1987) long-term zooarchaeological research in southern Africa centered on changes in animal, evolution, and human predation patterns through the Pleistocene. A key focus was changes in taxonomic abundances, which in turn rely on taxonomically identifiable. He quantified and compared datasets using MNI, to counterbalance possible differences in NISP created by differential transport of small vs. large bovid carcasses to central places by hominins.

Consistently applied, and with attention to possible in stratified sites (Chap. 18), this is a time-honored approach to taxonomic abundances. Klein's approach to estimating MNI relied upon counts of long bone epiphyses, which subsequent research on carnivore modifications (e.g. Marean and Spencer 1991; Marean et al. 1992) has shown can be less useful for estimating limb segment frequencies than are limb bone shafts (Chaps. 12 and 21). If Klein had instead been interested in reconstructing transport and processing decisions or site formation, he might well have given more attention to less identifiable specimens as well as to tallying modifications to identifiable and nonidentifiable specimens, as did Klein's student Richard Milo (1998) and Marean et al. (2000) in dealing with South African archaeofaunal samples. In these research projects, combinations of NISP, MNI, MNE, and counts of various modifications were used. Marean et al.'s (2000) work in this area will be discussed further in Chaps. 11 and 12.

Much of Grayson's (e.g. 1984b, 1991, 1993, 1998, 2000, 2011) research with Great Basin faunas has dealt with questions of paleoenvironments, paleobiogeography, and evolution, using archaeofaunas from stratified sites. This required a comparative measure of taxonomic abundance not affected by MNE's or MNI's problems with "aggregation effects" in stratified sites, as discussed in Chap. 18. Grayson deemed NISP to be a more reliable measure of abundance than MNI in this situation. Analyzing the rodents and other very small vertebrates that formed the basis of his paleoenvironmental inferences, Grayson could also assume that these were not subject to differential body segment transport by humans, but only to the taphonomic effects of consumers, primarily birds of prey (Chap. 13).

In my own comparisons of non-stratified early pastoralist sites in East Africa in the 1980s, I opted to use MNI. I deemed that, in the absence of aggregation effects, MNI would help correct for biases introduced into the samples by differences in processing and transport tactics on carcasses of domestic species killed near camp versus those wild species killed farther away. However, for other questions, such as the specific nature of those transport and processing decisions, I would use NISP and MNE, understanding their properties and limitations.

To rephrase Lyman's (1994b) point, the quantitative tool must be appropriate to the goals and "target" of the research. Just as no archaeologist would select a trowel to remove a meter of overburden from a site, so, too, no sensible zooarchaeologist should use inappropriate quantitative measures to further her or his specific research goals. Discussion of these basic counting units' pros, cons, and statistical applications will be continued in more detail in Chap. 18.

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Part IV
Identifying Causal Process, Effector, Actor

Chapter 11
Human, Animal, Geological Causes of Bone Breakage

As Chap. 2 described, broken long bones from paleontological and archaeological sites were a controversial topic for over a century. In North America and in Africa, they inspired much of the first work in zooarchaeology as a rigorous discipline, including early experimentation with modern analogues. This chapter begins with early archaeological research on bone fracture in the twentieth century, showing early researchers' lack of understanding of bone as a material and failure to seek similar outcomes produced by other actors. This highlights the need for research that situates experimental design and findings into biologically contextualized interpretive frameworks. Its next section outlines basic principles of bone biomechanics, elucidates how redundant patterns of bone fracture can be determined by intrinsic properties of the bone elements themselves as they respond to stress, rather than only the type of actor inflicting the stress. The following section surveys bone breakage patterns from several perspectives, outlining common descriptions of bone fracture shape and fracture surface texture, focusing especially on long bones. This also discusses how bone condition influences fracture shape and break surface texture, which provide valuable taphonomic information. It also introduces a theme that runs this set of chapters: how the stress an actor is able to apply varies according to different-sized animals processed.

11.1 Bone Fracture and Hominins: A Brief History

Widely published early research set the tone for bone fracture analysis for nearly 40 years. In the 1930s, French prehistorian Abbé Henri Breuil visited China and examined broken mammal bones associated with stone tools and *Homo erectus* remains at the "Peking Man" site near Zhoukoudian. Breuil (1938, 1939) cited common spiral fractures (Fig. 11.1) on long bones as proof of *Homo erectus* tool making, calling these bone daggers. As outlined in Chap. 2, Dart (1949, 1957, 1959) argued for deliberate tool production by *Australopithecus africanus* in South Africa,

D. Gifford-Gonzalez, *An Introduction to Zooarchaeology*,
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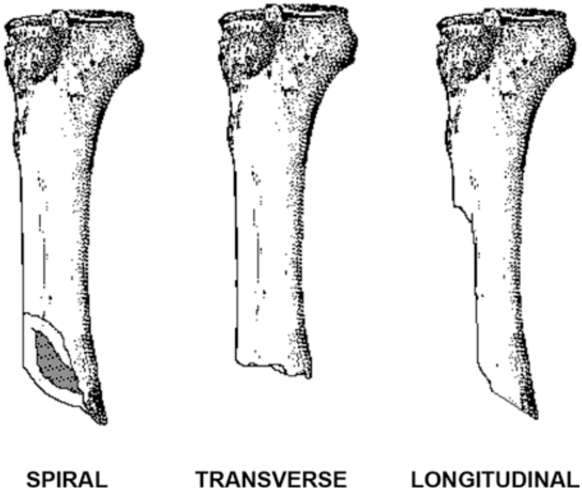

Fig. 11.1 Diagrammatic representation of spiral, transverse, and longitudinal fractures on a ruminant radius. The spiral fracture shows the winding of the break around the shaft of the bone. (Illustration by the author)

based in part on presence of spirally fractured long bones. He argued these could only be produced by a deliberate, "crack-and-twist" technique by hominin actors. A parallel argument from spiral fractures emerged in the Americas among archaeologists investigating the antiquity of human habitation. In Canada's Yukon, several researchers became convinced that spirally fractured long bones in Pleistocene river gravels testified to early human habitation, despite a lack of stone tools or archaeological sites (Jopling et al. 1981).

11.1.1 Actualistic Research on Bone Breakage

In response to these claims, Africanist and North Americanist archaeologists undertook experiments to assess the origins of spiral and other fractures on long bones. Some of these early experiments led to major advances in our understanding of bone breakage; others were not so well developed. Experiments by Hind Sadek-Kooros (1972) showed that "crack-and-twist" methods such as those Dart described could indeed produce spiral fractures on long bones. Sadek-Kooros's implicit assumption was that, because she could produce such helical breaks on bone, only humans could have made them on long bones. Moreover, she asserted that tool production was the ultimate goal of such bone breakage. In fact, both these points are questionable because she did not investigate other ways in which spiral fractures could be produced.

Bonnichsen (1973, 1979) experimentally produced spiral fractures using stone percussors on glass tubes and bone shafts, meticulously describing the force conditions that led to these breaks. His experiments showed that internally consistent glass cylinders broke in a helical pattern as the force wound around the tube, regardless of the type of loading. His observations of marrow extraction among contemporary Cree Indian people convinced him that spiral fractures could be by-products of food processing, and not solely of tool making. Early in his investigations, Bonnichsen nonetheless believed that only humans could produce spiral fractures, and they therefore were proof of human intervention, even without other archaeological indicators. Like Sadek-Kooros, Bonnichsen did not evaluate whether non-human agents, especially carnivores, could also produce them.

Building on this earlier work, Gary Haynes (1980, 1983) conducted actualistic research on bone breakage by wild and captive North American carnivores and bison trampling and rolling on older bones, repeatedly monitoring damage to large artiodactyl carcasses in the wild. Haynes reported spiral fractures on fresh bones exclusively processed by wild carnivores and herbivores. Simultaneously, paleontological researchers documented spiral fractures in a Miocene North American paleontological deposit formed before emergence of the Homininae (Myers et al. 1980).

Brain compared "osteodontokeratic" specimens to elements from leopard and hyena lairs, fed to captive carnivores, and processed by Khoikhoi pastoralists in what is now Namibia (Brain 1967, 1969). Brain (1981) also demonstrated that carnivore gnawing, culinary processing, and ungulate trampling produced element frequency patterns like those that Dart argued could only be produced by hominins' selective collection. Others researching East African contemporary landscapes and animals to elucidate fossil site formation made similar findings: Behrensmeyer (1975), Hill (1975), and Gifford (1977) documented spiral fractures on mammal bones not processed by humans, as well as the existence of "biased" element frequencies in contexts unaffected by humans.

Morlan (1983) aimed his actualistic research specifically at assessing the Yukon evidence and established that non-human actors could produce spiral fractures. Thorson and Guthrie (1984) evaluated whether freezing and thawing of rivers could break and otherwise modify bones by simulating bones being carried along during a spring ice thaw and break-up. These experiments showed that non-intentional impacts could produce spiral fractures and polished edges on break surfaces, evidence previously thought to be "proof" of human presence in the Pleistocene Yukon. Johnson (1982) and Johnson and Holliday (1986) excavated Paleoindian and later sites around Lubbock Lake, Texas, recovering many broken bones, including some imputed to be "expediency tools." Her experiments on determinants of bone fracture (e.g. Johnson 1985) are discussed in a later section of this chapter. Over the same period, critical analyses of such breakage that reported on non-human contexts (e.g. Lyman 1984; Richardson 1980).

In sum, actualistic investigations in the 1970s and 1980s established that spiral fractures occur in nature as well as through human intervention, showing that spiral breakage does not require the "crack-and-twist" method. When humans do cause spiral fractures, it is often as a by-product of marrow extraction rather than deliberate tool manufacture. Today, a multivariate approach to distinguishing actor in bone assemblages is taken, including not only fracture shape and break surface texture but also diagnostic bone surface modifications such as tooth marks or percussion-related damage. The balance of this chapter reviews basics of bone fracture and how breakage patterns have been discussed and described in zooarchaeological analysis.

11.2 Biomechanics of Bone

The biomedical and forensic research literature offers zooarchaeologists relevant information on bone as a material and its responses to stress. This discussion focuses on mammal elements, the most common osteological elements encountered in most archaeological sites. Bird, fish and reptile bones have different osteological organization, and less is known about their responses to the stresses outlined in this section. This discussion also focuses on long bones, the subjects of much attention in zooarchaeological research and very well studied in medical and bone mechanics research. Skeletal elements of the arm and leg are liable to injury in human bodies, which has produced a rich medical literature. Those interested in an entry point to bone biomechanics are recommended to visit the online "Bone Curriculum" sponsored by the American Society for Bone and Mineral Research (2008), a good resource for this and other fundamentals on bone: http://depts.washington.edu/bonebio/ASBMRed/ASBMRed.html.

11.2.1 Bone as a Material Under Stress

Terms drawn from materials science help understand the mechanics of bone breakage. *Stress* is the amount of force applied to a material, measured as weight per unit of area. Stress is quantified in millions of pascals (Mpa), which express a ratio of weight to unit area, in that 1 Pa = kilonewtons per mm^2 (Martin et al. 1998). In a whimsical tribute to the founder of classical physics, a newton was traditionally defined as the stress caused by an average apple's weight (0.1 kg) resting on a square meter of tabletop. Thus, 1 MPa = 10 kg per cm^2 (ASBMR 2008). The application of stress to a deformable body is called *loading*. Loading produces displacement of particles in the stressed object, which causes changes in shape of the body to which it is applied (Evans 1957). This is called *deformation*.

Strain is a measure of the deformation of a stressed body (Fig. 11.2). The degree of deformation is expressed in units of length, as a ratio of the deformed length of the object to its original length. The *stiffness* or *rigidity* of a material is expressed as the load needed to deform it a specified amount (Martin et al. 1998). If the stressed body recovers its original shape after the stress is removed, as does a soft rubber ball after downward pressure is released, this is called *elastic deformation*. If the stressed body instead takes on a shape different from its original one after the stress is removed, as would a similar-sized ball of clay subject to the same loading as on the rubber ball, this is called *plastic deformation*. As a two-phase (collagen/hydroxyapatite) material, bone is liable to both elastic and plastic deformation.

Every material has both a specifiable limit to its elastic deformation, called the *yield (stress) point*, and a limit to its plastic deformation, past which it breaks, or *fails*. This is called the *(ultimate) failure point*. Figure 11.2 shows these relationships, using a hypothetical material to which increasing levels of stress are applied.

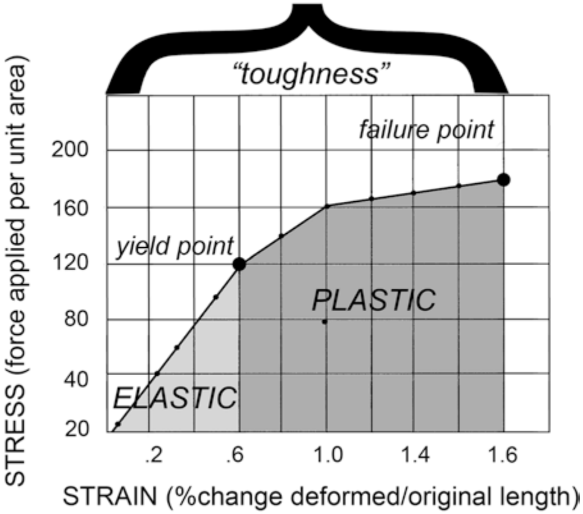

Fig. 11.2 Graph showing zones of elastic and plastic deformation, with the yield and failure points, of a body of a hypothetical deformable material. (Figure by author)

Stress applied (loaded) to the body produces deformation. Up to a certain level of loading, the material deforms and then "rebounds" to its original shape when loading stops. The chart shows this *elastic strain zone* (light shading in Fig. 11.2), which represents the range of quantifiable and predictable stress-strain relationships in which the body displays *elasticity.*

Past the yield point, the stress-strain curve becomes more level. At a point unique to each material, increasing stress reaches the point of the body's *ultimate failure point*. The amount of post-yield strain that a material can withstand before it fractures is called its *ductility.* A material that sustains very little post-yield strain before fracture is *brittle*, whereas on that sustains much post-yield strain is *ductile.* The total area encompassing both elastic and plastic deformation under the stress-strain curve describes the material's *toughness*, that is, its ability to absorb energy while resisting catastrophic failure.

The elasticity of a material can be expressed as *Young's modulus*, or the *modulus of elasticity*, which distills a material's ratio of linear stress to linear strain into a single number, expressed in Mpascals.

$$\mathrm{E}(\mathrm{Mpa}) = \frac{\mathrm{stress}}{\mathrm{strain}}$$

In bone, *Young's modulus* is given in gigapascals, GPa = 10^9 pascals (Martin et al. 1998). For all materials, two other moduli can be calculated to describe the response to compressive (bulk) and shear (torsional) loading (see Fig. 11.3), but these will not be detailed here, as the modulus of elasticity alone can illustrate the main points of this section.

With the information outlined above, one can appreciate the results of mechanical studies of bone fracture. Bone is an *anisotropic* material, that is, it has a "grain"

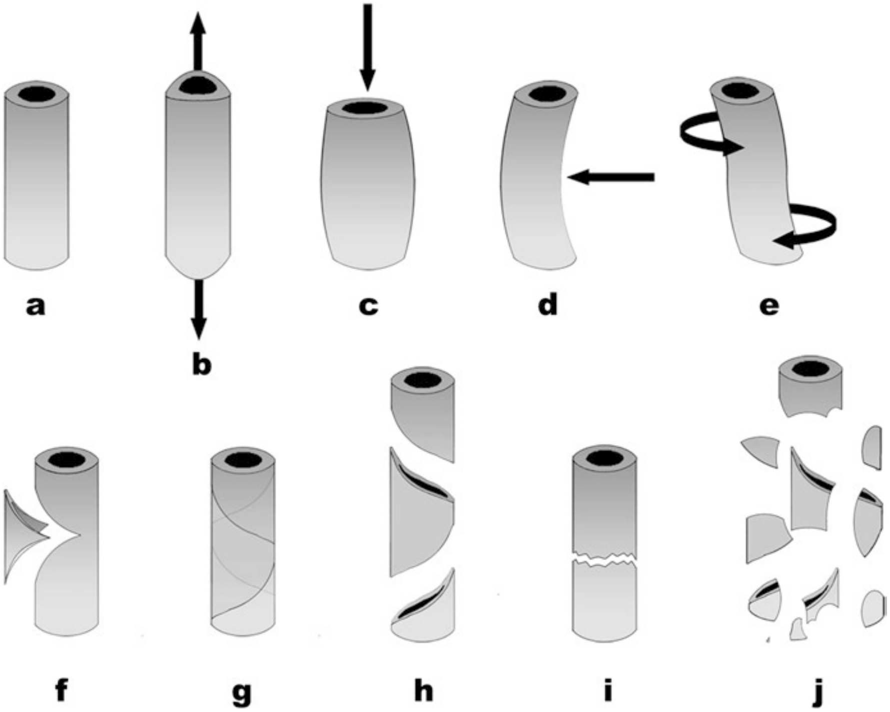

Fig. 11.3 Diagrammatic representation of stress and strain on bone cylinders and possible outcomes. (**a**) A hollow cylinder of bone in unstressed state. (**b**) The cylinder deforming under vertical tension. (**c**) The cylinder deforming under vertical compression. (**d**) The cylinder deforming under lateral compression. (**e**) The cylinder deforming under torsional stresses in two planes. (**f**) A butterfly fracture, normally the result of bending stresses on a long bone (**d**). (**g**) Spiral fracture lines, in which the force fronts of stress loaded on the cylinder wrap around the long bone in helical fashion. (**h**) Fragments of the cylinder formed when cracks perpetuated by the force fronts meet each other. (**i**) Transverse fracture, where the ability of the cylinder to transmit and disperse stresses longitudinally fail, and a crack perpetuates laterally across the cylinder. (**j**) Comminuted fracture, in which the force conditions of the stress on the cylinder are so much greater than its toughness that multiple failures occur (Illustration by the author)

or internal structure, created by the organization and orientation of its osteons (Chap. 4). This contrasts with *isotropic* material, such as glass, which comprise consistently arranged, homogeneous constituent particles. Bone's internal structure governs its responses to stress depending upon the direction in which force is loaded in relation to its internal structure. One can find many analogues for this in modern engineering, such as incorporation of rebar running in the main direction of anticipated stresses in reinforced concrete.

Stress can strain and deform living bone occur along three dimensional axes (Currey 2002: 28–34). Unlike an isotropic glass cylinder, bone's anisotropic qualities can in effect dictate different levels of elasticity for the same element, depending upon the directionality of the stress. Table 11.1 gives examples of simple loading

Table 11.1 Comparative moduli of elasticity and ultimate compressive stress, in human and bovine cortical bone, showing longitudinal and transverse directions, expressed in gigapascals (GPa), or 1,000,000,000 pascals, and megapascals (Mpa), or 1,000,000 pascals

Bone property	Human	Bovine
Elastic modulus, GPa		
Longitudinal	17.4	20.4
Transverse	9.6	11.7
Bending	14.8	19.9
Compressive ultimate stress, MPa		
Longitudinal	195	237
Transverse	133	178

From Martin et al. (1998: 137)

Table 11.2 Differing levels of elasticity and brittleness, expressed through the modulus of elasticity and the ultimate stress indices, with degree of mineralization for three different elements and taxa

Taxon/element	Modulus of elasticity (GPa)	Ultimate stress (MPa)	% Mineralization
Whale petrosal	31.3	27	86%
Cattle femur	13.5	148	67%
Deer antler	7.4	158	59%

ASBMR (2008) and Currey (2002): 126, 131)
GPa gigapascals, *Mpa* megapascals

(as opposed to torsional loading, see below), showing that transverse loading to long bones causes failure at lower levels of strain. Hominins have taken advantage of this property of long bones for millions of years, striking them at right angles to the orientation of their osteons, in which plane these elements are more likely to break.

Moreover, specific bone elements differ in their degree of elasticity and brittleness, as shown in Table 11.2. A whale petrosal has a steep slope to its yield point yet a low ultimate failure point, due to its brittleness, which in turn stems from its proportionately higher bioapatite composition. Deer antler has a low modulus of elasticity, reflecting this material's shallow slope to its yield point, and possesses the highest ultimate stress point, due to the high proportion of collagen content of the element. Both sorts of variability are the functional outcomes of the life habits of particular species, and some of these have been manipulated by hominins for millennia. Due to its elasticity and high ultimate failure point, antler was adopted as a flexible and durable percussion tool in the so-called "soft hammer" percussion technique that produced many late Palaeolithic tools.

11.2.2 Stress and Strain in Bones

Skeletal elements undergo tensile (stretching), compressive, and shear (torsional) stresses (Fig. 11.3a–e) during life. Stresses occur during everyday locomotion and food acquisition and processing, but if an animal is to survive, skeletal parts must also resist stresses such as falls, blows to the body, or exceptional efforts to escape a predator. Depending on the direction(s) of the stress in relation to osteonal organization and the level of force applied, an element may reach its ultimate failure point and crack. Biomedical research has shown that bone microcracks are common occurrences in living animals and that bone deposition is rapidly mobilized to heal them (Nalla et al. 2003; Martin et al. 1998:181–182). However, if such levels of stress continue or increase, cracks will perpetuate.

In living bones, most such stress transmits along the orientation of the collagen fibers, which have developed in response to these. In more or less cylindrical elements such as long bones, stress is transmitted along the generally lengthwise osteonal structure of the compact bone shaft (Fig. 11.3g). As force moves through the bone, it also tends to move helically, just as it does in isotropic materials, skipping laterally across the osteons. If the force of the stress has reached the shaft's failure point, an oblique, winding crack propagates around the circumference of the shaft in a spiral manner. Where cracks cross with one another, they may breach the wall of the bone completely, resulting in fragmentation (Fig. 11.3h). Spiral breaks of long bones often terminate as they wind around and meet together or end at the transition to cancellous bone tissue (see below).

If the stress loaded is so great that the bone cannot adequately transmit the force longitudinally, a more or less transverse crack develops through the shaft wall (Fig. 11.3i). Stress and strain conditions resulting in transverse fracture can vary: a very strong impact that exceeds the failure point can create a transverse fracture on fresh bone. Alternatively, a long bone's collagen fibers may have shortened postmortem, or the bone may have lost fluid from its interstitial pore space, both of which diminishes elasticity and the lengthwise transmission of force. Zooarchaeological aspects of this process will be discussed below in *11.3.6 Effects of Loading Levels on Breakage Morphology*.

Finally, the loading of force into the cylinder structure may be so great as to cause catastrophic failure of the shaft at many points, resulting in a comminuted fracture (Fig. 11.3j). Such fractures are typical of automobile accident injuries in humans and similar very strong blunt force traumas.

If the force front does reach the cancellous tissues at the end of the element, it is diffused through their system of trabeculae. Trabecular bone, while less elastic than cortical bone when measured as individual trabeculae, has an overall structural organization capable of absorbing high levels of stress without failure. Thus, individual spicules have a low modulus of elasticity, but in aggregate, trabecular bone's modulus of elasticity approaches those of cortical tissues (Currey 2002: 168–172).

Intertaxonomic comparative studies showed that different mammal taxa possess nearly identical peak functional strains (Biewener and Taylor 1986; Martin and Burr 1989; Rubin and Lanyon 1982). These found that, although peak bone stresses varied considerably within a single skeleton as well as among species according to body mass, vertebrate skeletons adapt to reducing bone strain to levels that enable continued element integrity and mechanical function.

However, other research has suggested that intertaxonomic differences in mammalian bone microarchitecture (Chap. 4) can influence fracture patterns and break surface appearance in cases of structural failure. Wang et al. (1998) noted significant break surface differences, according to the microstructure of osteons, among isolated specimens of human, baboon, dog, rabbit, and bovine bone. As might be expected from an evolutionary perspective, humans and baboons possess similar bone organization and structural failure properties, with canine bone more similar to these two than all three were to bone of rabbits or the plexiform bone of bovines. Wang et al.'s work aimed to better define which taxa are the best models for human bone fracture. Nonetheless, zooarchaeologists should consider that some variation of fracture surface properties, especially as revealed under high magnification, may be attributable to intertaxonomic variation, rather than solely to postmortem timing of the break. Martiniakova et al. (2006) discuss differences in microstructure of osteons among various species in a forensic context.

11.2.3 Types of Loading

The biomedical literature describes three types loading that can produce structural failure, corresponding to some degree to the types of failure represented in Fig. 11.3:

1. *Static*: gradual increase in pressure until the bone undergoes structural failure. This can apply to compressive or tensile loading.
2. *Dynamic*: sudden impact loads the bone with stress that exceeds the failure point, either with cracks intersecting one another or through catastrophic structural collapse. This is normally compressive loading.
3. *Torsional*: twisting beyond the bone's ability to resist stress produces a crack and break.

Human and non-human carnivores obtain fat-rich yellow marrow from mature mammals' long bones by applying different types of loading to the bones. Carnivores normally use *static loading*. They begin by gnawing off the epiphyseal ends of the bones, in the process consuming nutritious red marrow and fat cells in cancellous tissues. They then squeeze the remaining bone cylinder in a vise-like grip with their back teeth. This may collapse the cylinder, permitting access to the marrow within (Binford 1981; Binford and Bertram 1977). This chapter examines details of such static loading. Hominins gain access to marrow in the endosteal spaces by striking the diaphysis with a stone or other percussor, usually at right angles to the long axis of the bone. This is an example of *dynamic loading*. The compact bone wall struck with a hammerstone will display characteristic evidence of the loading, including notching, as discussed in Chap. 13.

11.3 Bone Breakage Patterns

Each type of skeletal element responds to stresses according to its distinct osteonal arrangement at both gross and ultrastructural levels, which align to absorb the strains in a vertebrate's body during life. This internal organization of osteons in a given element of a specific taxon will vary little inter-individually, so elements of that type and taxon are likely to respond in similar ways to postmortem stress. Thus, consistency of osteonal structure is responsible for much of the redundant patterning seen in assemblages of broken long bones and other bones. Fresh humeri, usually fracture in a short spiral along the shaft (Fig. 11.4). Tibiae, by contrast, often break in a more longitudinally extended spiral, with a longer section of the break extending from the loading point (Fig. 11.5). Such consistencies in the break forms of specific elements led early researchers (e.g. Breuil 1939; Kitching 1963) to infer deliberate hominin tool production.

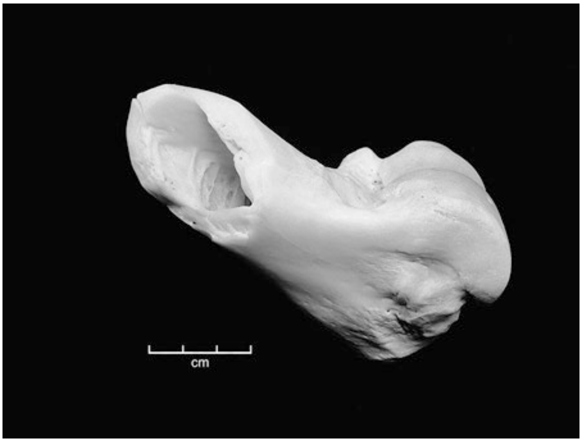

Fig. 11.4 A distal cow humerus, showing a spiral fracture on fresh bone. The break terminates as the break surface winds around the bone and the point at which the perpetuating crack of the force front meets the initial crack. Arrow shows termination point (Photo by Don Harris of experimentally broken specimen from the author's laboratory collection)

Fig. 11.5 Cow tibia from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya. Shows oblique fracture typical in fresh specimens of this bone (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September 1973)

11.3.1 Long Bone Break Classification Systems

While debates over agency behind long bone breakage were at their heights, researchers created detailed systems for describing long bone break shapes and textures (Sadek-Kooros 1972; Biddick and Tomenchuk 1975; Haynes 1983; Johnson 1985; Morlan 1984; Marshall 1986). Further understandings from taphonomic and biomedical studies have led most zooarchaeologists to invest less energy in constructing and using elaborate descriptive systems for all fractures in an assemblage, but many still record not only shapes of long bone fractures but also break surface texture and angle with relation to the outer surface of the diaphysis (shaft).

The classic terminology, derived from the biomedical literature, separates long-bone fractures into three shapes:

1. *Spiral fracture*: a break in which the force front wraps around the bone while traveling along it, producing the helical form as one propagated crack created meets another break surface on the bone.
2. *Transverse fracture*: a break in which the force front travels more or less directly across the cross-section of the bone, creating a break at right angles to the long axis of the bone.
3. *Longitudinal fracture*: a break transmitted along the bone in a longer, but often helical, pattern, producing a fragment with a longer break surface.

The point at which a break ends is called the *break termination*.

Theoretical grounds exist for expecting long bones to break transversely when levels of stress far exceed their failure points. Samples of fully hydrated, fresh bone tissue have been shown to break transversely when subjected to dynamic loading perpendicular to the predominant alignment of collagen fibers in the specimen (Bonfield and Li 1966). With regard to the texture of the break surface, Bonfield and Li (1966) report jagged fracture surfaces on transversely impact-loaded fresh bone specimens. Large carnivores could exert these levels of static or torsional loading on the bones of smaller prey, as could hominins wielding percussors on elements of animals considerably smaller than their own body size.

11.3.2 Break Shape Descriptive Systems

Zooarchaeological researchers have noted one problem with classic medical terminology: it uses a few terms to describe multiple break features that do not necessarily covary. These include: the overall outline shape of the break in relation to the long axis of the bone, the angle of the break surface in relation to the outer surface of the bone, and the texture of the break surface itself, which reflects underlying structural organization as well as (Morlan 1984; Todd and Rapson 1988; Villa and Mahieu 1991). Several researchers have sought to transcend the historically weighted terms derived from the medical literature (spiral, transverse, longitudinal).

Biddick and Tomenchuk (1975) devised a system for mapping break morphology in two dimensions that permits replicable measurement and statistical comparison. Karen Lee Davis (1985) developed a detailed system based on alphabetic codes for selections in three variable classes. See Lyman (1994: 318–224) for a detailed review of these systems.

Researchers working with well-recovered assemblages have had to consider how to describe long bone diaphysis fragments lacking epiphyses in terms of how much of the bone these fragments represent. A common practice is to estimate how much of the circumference of the bone is represented (Bunn 1989; Marean and Spencer 1991; Villa and Mahieu 1991).

In the absence of any universally adopted for describing bone breakage, researchers should employ a system that does not *a priori* impute actor and context of breakage (as did Sadek-Kooros's), is efficient for describing large samples, and permits comparison with specimens analyzed in others' systems. My own view is that, now that we understand that break morphology in and of itself cannot be used to infer actor and context, extraordinary levels of descriptive detail may not be needed to describe and compare bone breakage patterns of interest to archaeologists and taphonomists. Rather, we need descriptions that allow others to assess our classificatory methods and results, in much the same way that we describe distinctive traits of species, in order that other researchers can assess the taxonomic classification decisions we made. In the case of long bone fracture studies, an emerging standard common practice minimally uses: common descriptive terms for break shape (e.g. spiral, longitudinal, transverse), descriptions of break surface texture (e.g. smooth, stepped, jagged, see below), completeness of the circumference of the cylinder of each fragment (e.g. 100%, 50%, 25%), and angle of the break, relative to the surface of the element.

11.3.3 Effects of Bone Condition on Break Shape

In her experimental work, Johnson (1985) noted that dynamic loading of fresh diaphyses transmitted force along the orientation of collagen bundles in the bone, resulting in helical movement of fracture fronts and, as a result, spirally fractured bones. However, she found that experimental bone specimens air-dried before breakage but not otherwise modified displayed a higher proportion of more transversely oriented breaks, relative to the long axis of the bone. Such specimens also displayed a more stepped break surface. Johnson termed these "horizontal tension failures." Transverse breaks usually result from an interaction of bone tissue condition and the level of loading stress applied. Collagen gives bone its elasticity, and postmortem processes that affect it will alter an element's elasticity. Drying (loss of extracellular bone fluid) can also influence bone's response to stress by reducing its elasticity.

The breakdown of long bones' longitudinal collagen fibrils into shorter segments occurs gradually in most postmortem specimens. Heating accelerates this process,

Fig. 11.6 Refitted transverse fracture on a zebra (*Equus quagga boehmi*) radius shaft from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya. Shaft shows darkened sections of heat-altered bone surface, transverse fracture with jagged break surface on the posterior wall of the diaphysis (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September 1973)

swiftly reducing the element's elasticity, and the tensile, compressive, and shear moduli of bone. Shortened collagen strands permit propagation of more transverse and jagged breaks. If the direction of loading to the bone is perpendicular to its longitudinal axis, as it is in most human dynamic loading, shortened collagen bundles allow fracture fronts to move across the diaphysis (Fig. 11.6).

Ethnoarchaeological evidence for the effects of heating on breakage patterns exists. Bonnichsen (1973) reports that Calling Lake Cree informants prepared defleshed long bones for breakage by heating them and allowing them to cool. Informants said heating facilitated shaft breakage. Oliver (1993) and Gifford-Gonzalez (1989) discerned higher frequencies of transverse breaks on large animal long bones as well as more jagged, stepped break surfaces in ethnographic bone displaying evidence for thermal alteration and collected soon after human processors had discarded it, thus eliminating weathering as a causal process. Little experimental work has been published on effects of cooking on tensile strength of entire mammal bone elements. Bonfield and Li (1966) exposed long-bone segments to impact and tensile stress at temperatures ranging from −196 to 500 °C. Within the range of 50–100 °C (realistic boiling and roasting temperatures), the authors found that heating did not alter bone's fracture properties. This experiment may not be so relevant to cooking because specimens were quickly heated and then broken, with no effort to maintain the bones at the target temperatures for some span of time before impacting them. This treatment thus fundamentally differed from those of roasting, baking, or boiling (see Chap. 14 for more detail). Richter (1986) observed that collagen strands in fish bone begin to break down when baked at temperatures between 60 and 100 °C for only 30 min. In fish bones boiled for 30 min, the collagen was completely denatured. Richter also notes that collagen in mammal bone may be somewhat more protected from the effects of heating than it is in thinner fish elements.

Fig. 11.7 A nearly transverse fracture on the shaft of a weathered cow femur, showing break surface transecting the columnar units into which the bone had weathered. Site 105 Dassanetch pastoralist camp, near Koobi Fora, East Lake Turkana, Kenya, 4 weeks after the site was abandoned. However, the extent of weathering on bone suggests several years' exposure to elements, unlike the preponderance of specimens from the site. (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September 1973)

Karr and Outram (2012a, b) report on experiments with bone fracture, using "fresh," a term they rigorously explore, horse and cattle bones subjected to closely controlled temperature regimes. They found that, when broken by dynamic loading, specimens displayed differences in break shape (helical vs. transverse), length of the break and break angle relative to the surface of the bone, break surface texture (see below), and number of fragments produced, all according to the temperature (and, by implication, levels of humidity) of the environment in which bone had been stored. They noted that bones in hot and dry environments change in fracture morphology most swiftly, whereas those frozen once and then thawed changed at the slowest rate. Their closely controlled study poses a cautionary note for designing experimental research using "fresh" bones and supports much anecdotal data on bone breakage in the ethnoarchaeological literature.

Weathering of bones on land surfaces, to be described more fully in Chap. 15, is mediated by breakdown of collagen fibers (Behrensmeyer 1978; Hare 1980). Weathering divides osteonal bundles (Tappen and Peske 1970), which condition the element's response to stress. As with heating, loss of collagen integrity lowers the element's elasticity, and transverse breaks are more common in weathered bone. Break surfaces of these broken long bones can visibly differ from those produced on heated bone, as the weathered bone texture is exposed (Fig. 11.7).

Post-depositional but pre-mineralization alteration in collagen structure and content may also dictate bone fracture shape. Villa and Mahieu (1991) compared Neolithic human bone breakage patterns from La Baume Fontbrégoua, Provence, with two Neolithic cemetery assemblages of bones intact when they were buried. The Fontbrégoua human bones received the same culinary processing and disposal as non-human fauna and appear to represent a case of cannibalism (see Chap. 14). Broken bones from the two Neolithic cemeteries displayed fewer spiral fractures than those of Fontbrégoua and a higher proportion of jagged break surfaces, in contrast with Fontbrégoua's smoother break surfaces. This suggests that the cemetery samples underwent breakage after burial and loss of collagen, whereas the Fontbrégoua sample was fractured while the bone was relatively fresh.

11.3.4 Bone Condition and Fracture Angles

Marean et al. (2000) took a roughly parallel approach to that of Villa and Mahieu in describing the relation of bone condition to fracture shape and angle, using Capaldo's (1997) useful distinction between the "nutritive" and "non-nutritive" phases of vertebrate remains' taphonomic histories. This divides paleontology's "biostratinomic" phase into an interval during which skeletal elements are liable to various actors' attempts to gain sustenance, and that when bones are constituents in landscapes that may be incorporated into geological deposits. Skeletal elements in the nutritive phase are usually moist, rich in collagen, may be greasy, and contain within-bone nutrients of the types discussed in Chap. 3. Those in the second phase are increasingly dry, collagen- and grease-depleted, with fewer consumable tissues.

Marean et al. (2000: 208) used several sets of fresh long bones, and dry long bones to experimentally produce hammerstone-mediated fractures, carnivore-mediated fractures, and combination of carnivore processed fragments of hammerstone-broken assemblages. Neither the actor (humans *vs*. carnivores) nor the type of loading (dynamic hammerstone vs. static carnivore), displayed statistically significant differences in frequencies of breakage types, with a single exception. Oblique fractures of fresh bones in hammerstone-only samples differed significantly from hammerstone-to-carnivore samples (Marean et al. 2000: 208). Statistically significant differences in breakage types emerged between fresh and dry bone samples, with more right angle and transverse breaks in the dry bone samples (Fig. 11.8).

Karr and Outram (2012a, b) report on experiments with bone fracture, using "fresh," a term they rigorously explore, horse and cattle bones subjected to closely controlled temperature regimes. They found that, when broken by dynamic loading, specimens displayed differences in break shape (helical vs. transverse), length of the break and break angle relative to the surface of the bone, break surface texture (see below), and number of fragments produced, all according to the temperature (and, by implication, levels of humidity) of the environment in which bone had been stored. They noted that bones in hot and dry environments change in fracture morphology most swiftly, whereas those frozen once and then thawed changed at the slowest rate. Their closely controlled study poses a cautionary note for designing experimental research using "fresh" bones and supports much anecdotal data on bone breakage in the ethnoarchaeological literature.

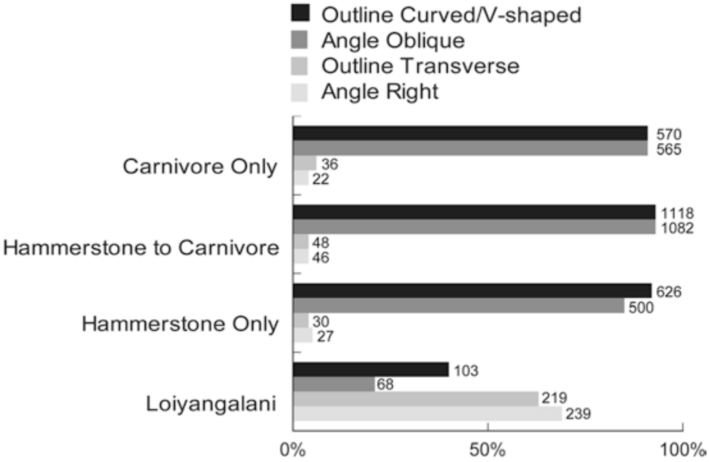

Fig. 11.8 Graphic by Thompson (2005: 85, Fig. 11), showing Marean et al. (2000) fracture outline and angle data for carnivore only, hammerstone only, and hammerstone-to-carnivore experimental breakage of fresh long bones. The lowest register presents Thompson's data from specimens recovered from the open-air Middle Stone Age Loyangalani River Site, which illustrates quite divergent patterns of post-deposition and post-mineralization bone breakage patterns. Used with permission of the author and *Journal of Taphonomy*)

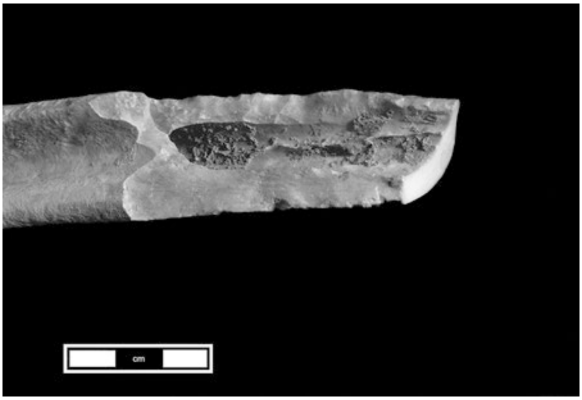

Fig. 11.9 Post-mineralization break across a fossilized deer metatarsal from Pliocene paleontological deposits in the Nihewan, western Hebei Province, Peoples Republic of China. Note the flat break surface and its different color from the rest of the older, undulating break surface, which shows hackle marks developed during the original fracture of fresh bone. Note as well shallow flakes and tooth scores from ancient carnivore gnawing (Photo by Don Harris of specimen collected and donated by Dr. Wei Qi of the Institute for Vertebrate Paleontology and Paleoanthropology, Beijing, in possession of D. Gifford-Gonzalez)

Morlan (1984) noted that mineralized ("fossilized") long bone breaks according to its diagenetically altered mineral structure rather than according to its original osteonal organization (Fig. 11.9). According to Morlan, the shape of the break can be straight, transverse, or longitudinal, but spiral fractures are quite rare. The color of post-depositional fracture surfaces often contrasts with the bone's outer surface.

11.3.5 Bone Condition and Break Surface Texture

In addition to overall break shape, the surface texture of the break may be characterized by terms used to describe lithic fracture: smooth, rough or pebbly, stepped, and so forth. Fractures are taking a cross-section of a bone as they transect it, the texture of a break surface can be seen as an index of collagen loss and is a clue to the taphonomic history of a specimen. An experimental blind-test study in human forensics suggests that break surface texture is an important key to the timing of fracture in an element's postmortem history. Wieberg and Wescott (2008) asked 22 forensic anthropologists to assess whether 10 experimental specimens were fractured perimortem or postmortem. Participants were asked to report specific criteria they used to assess timing of breakage. Scores for the timing of bone fracture in the blind test varied from 30% to 100% correct, with an average score of 68%. Participants who used fracture surface texture as a key trait in their assessments obtained the highest correct scores (Figs. 11.10 and 11.11).

Breaks on fresh bone are usually smooth in texture. Bone that has undergone destruction or shortening of collagen fibers by heat or weathering displays a spectrum of rougher ("pebbly") to jagged or stepped break surfaces. The latter can be

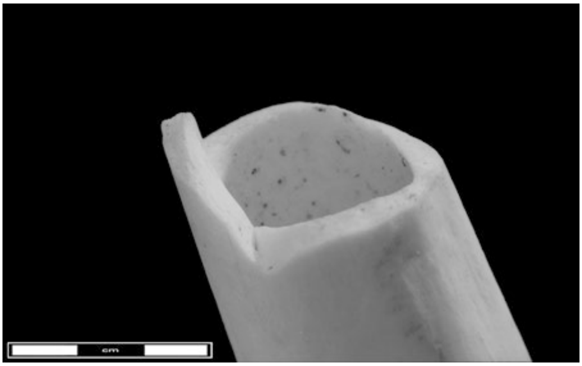

Fig. 11.10 Caprine (sheep/goat) femur shaft from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya, showing near-transverse fracture across shaft, with evidence for thermal stress on break surface (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September 1973)

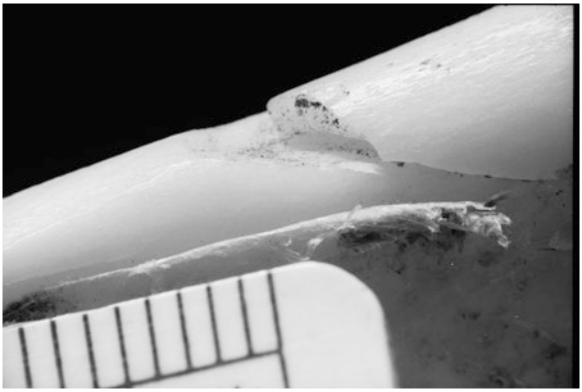

Fig. 11.11 Chop mark on diaphysis, showing the *panga* chop mark and the line of the fracture surface running on from where this terminates. Scale: lines are millimeters (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September 1973)

distinguished from the former once one understands the progression of weathering in mammalian bone (Chap. 15).

Another feature on fresh bone break surfaces are ripples, or *hackle marks* (Fig. 11.7), surfaces that reflect percussive force rippling through the bone wall as it perpetuates a crack (Johnson 1985). Much like concentric rings in conchoidal fracture of stone, hackle marks run away from the loading point.

11.3.6 Effects of Loading Levels on Breakage Morphology

The relationship between the amount of stress loaded and a given element's ultimate failure point is another, seldom discussed factor in determining long bone break morphology. Vertebrates come in different sizes, and their bones' abilities to withstand stress vary with size. The same actor and effector, inflicting the same stress, can produce disparate effects on different-sized long bones. For instance, a strong human can probably snap a rabbit femur in two by bending it, but not even a very strong person could do the same with a horse femur. As in the hypothetical case of transverse fracture described in Fig. 11.2, the stress loaded is so great that strain in the element immediately reaches failure, resulting in a break perpetuating in the direction the force entered the bone. If this is perpendicular to the long axis of a diaphysis, a transverse fracture results. Likewise, the form that loading takes can affect break morphology and surfaces.

Blasco et al. (2014) struck a set of fresh cattle long bones against a stone anvil, which actions permitted loading greater force with this clubbing action than is possible with hammerstone loading. They report that rates of fracture form, fracture surface texture, fracture angles, and shaft circumference in diverged markedly from a comparison set of hammerstone-fractured bovine long bones. This study and its results will be discussed in detail in Chap. 13, but it can be noted here that fracture-by-clubbing produced higher rates of transverse fractures, jagged fracture surfaces, mixed rather than oblique fracture angles, and complete circumference fragments. In short, this method of dynamic loading long bones applied such force at the loading point that many elements immediately reached their failure points, without dispersing much stress longitudinally.

I reported relatively high rates of transverse fractures on larger (cattle and zebra) and smaller (sheep and goat) long bone specimens from a Dassanetch pastoralist camp at East Lake Turkana, Kenya (Gifford-Gonzalez 1989). However, I concluded that these outcomes actually reflected divergent processing histories for the two size classes. On larger animals' bones, transverse fracture shapes were often associated with signs of exposure to fire and jagged, stepped break surfaces (Figs. 11.6 and 11.7). Breaks on smaller animals' long bones, though transverse in relation to the elements' long axes, tended to be more helical in shape, and their surfaces tended to be smoother and more sinuous (Fig. 11.9). This probably resulted from dynamic loading to fresh, as opposed to heat-stressed, bone.

Table 11.3 Relation of bone condition to fracture outline, break surface texture, break angle, break termination point

Bone condition	Typical outline forms	Surface texture	Break angle	Termination location
Fresh or moist	Longer, high rates of spiral	Smooth	Acute, obtuse, or right	At or before epiphysis
Dry	Some spiral, more transverse,	Smooth to stepped	Acute, obtuse, or right	May go through epiphysis
Weathered	Transverse or longitudinal	Jagged	Obtuse or right	May go through epiphysis
Heated, cooled	Transverse	Jagged	Close to 90º	In compact bone
Mineralized	Transverse or longitudinal	Pebbly	Close to 90º	May go through epiphysis

A final factor should be considered in relation to fractures on long-bone shafts: notching or cutting as a means of facilitating bone breakage. Experiments have shown that notching inflicted perpendicular to the long axis of the osteons radically reduces a bone's ability to absorb the force of a blow, thereby increasing its tendency to break (Bonfield and Li 1966; Mengoni Goñalons 1982; see also Nalla et al. 2003). Notches apparently made to reduce the tensile strength of long bones have been found in archaeofaunas. Borrero (personal communication, 1987) reports notching occurred on about 70% of guanaco radioulnae in Patagonian forager assemblages. Notching is consistently associated with transverse fracture patterns; unnotched bones in the same Patagonian assemblages display spiral fractures. In the Patagonian case, notches were inflicted by sawing with a stone tool at right angles to the shafts near epiphyses. At the Dassanetch camp mentioned above and at Site 08, a Dassanetch foraging camp, long bones displayed transverse chop marks by metal bush-knives or *pangas* (Fig. 11.6). *Pangas* or hatchets simultaneously cut a notch in and dynamically load the diaphysis, facilitating transverse breakage.

Table 11.3 summarizes break form and surface texture data discussed here. An important point to bear in mind is that these variations in fracture patterns and break surface texture, while not necessarily pointing to a specific actor in the absence of contextual bone surface modifications, do provide important taphonomic information. These indirect signals of breakage while fresh, desiccated, or weathered are all, to repeat Sillen's (1989: 128) phrase, "part of the view" of site formation and, in some cases, of human behavior.

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Chapter 12
Mammalian and Reptilian Carnivore Effects on Bone

Chapter 11's discussion of bone fracture suggested that, given the strong structural influence on skeletal element fracture patterns, different actors are likely to produce similar break morphologies. Other taphonomic traces, usually bone surface modifications, often offer better resolution concerning the actor or actors involved. This chapter introduces modifications inflicted on bone by carnivorous mammals, including humans, and by crocodiles, the only reptile group for which bone modifications have been recorded. Carnivores consume blood, muscle, body fat, internal organs, fat and red marrow in pore spaces of cancellous bone segments, and yellow marrow in endosteal spaces. As they acquire these tissues, they modify and even consume bone tissue. The hyena family has evolved massive dentition, jaw musculature, and stomach acid that enable them to consume and digest bone, assimilating the collagen and fat in such tissue.

In the 1980s, definitive traits of carnivore tooth marks were distinguished from marks made by hominin tools. With a few notable exceptions (Binford 1981; Haynes 1980a), the first wave of literature on carnivore bone surface modifications were made by zooarchaeologists focusing on Plio-Pleistocene archaeofaunas. South American and Australian researchers working with Upper Pleistocene and Holocene archaeofaunas later contributed data from different carnivore communities.

This chapter begins with a general review of mammalian carnivores' processing vertebrate bodies, including carcass and bone consumption sequences. It then outlines specific effects of different carnivore families, relating these to their anatomy and the tissues they habitually consume. It ends by introducing factors that influence in-place destruction of skeletal elements by carnivores vs. their transport of elements to other locales, a topic discussed again Chaps. 19, 20, and 21.

For zooarchaeologists dealing with archaeofaunas from medieval Europe or plantation sites in the pre-Civil War United States, the effects of hyenas, wolves, and big cats might seem irrelevant. However, domestic dogs, especially those spurred by humans' practice of letting them fend for themselves, have been ubiquitous and exceptionally motivated bone processors in human settlements for much of the Holocene. Zooarchaeologists working when and where dogs may be present need to

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recognize signs of carnivore impacts on their bone assemblages. Furthermore, if researchers plan to use element frequencies in their analyses, they must construct the case for *excluding* destruction by dogs as a major determinant of assemblage structure, citing bone surface modifications and relevant contextual evidence. The simple absence of dog remains in an archaeofaunal sample is not proof their absence as a taphonomic agent, since disposal of dog carcasses is often culturally structured and may result in discard away from food debris.

Focusing as it does on the actor-effector level, this chapter will not address the controversies over the behavioral and ecological meaning of tooth mark frequencies in archaeofaunas. Patterns of aggregate archaeofaunal data will be taken up in Sect. 12.5.

12.1 Carnivore Effects on Prey Bodies and Bones: An Orientation

With the exception of vultures (Chap. 13), few vertebrates subsist entirely by scavenging. Vertebrate carnivores may hunt living animals and scavenge dead ones. Spotted and striped hyenas, popularly considered scavengers, actually hunt and scavenge. Kruuk (1972) found that quite a few lion "kills" were in fact hyena prey that were subsequently appropriated by lions. Without witnessing a kill, one cannot assume beforehand whether a predator obtained prey animals by hunting or by scavenging, which makes a term for obtaining an animal body, without stipulating how, very useful. I have used *carcass acquisition* and *carcass acquisition locale* (Gifford-Gonzalez 1993) as neutral terms that imply nothing about *how* an actor, human or non-human, took possession of an animal body, but simply that it did so.

Carnivores have a somewhat stereotyped sequence of consuming intact carcasses of larger prey, and the marks they leave will generally be parallel across various taxa, although the intensity and placement of marks may vary according to contextual factors and predator anatomical traits, as will be seen in the next section of this chapter. For instance, when scavengers consume remnants of a partially eaten carcass, the initial condition of the carcass upon encounter influences their handling tactics.

Zooarchaeologically relevant effects of carnivores fall into three categories:

1. *Modification* to bone surfaces as marks inflicted during kill and consumption. These were formerly called "tooth marks" or "gnawing marks," but greater specificity is now used.
2. *Destruction* of entire bone elements or of segments of elements during consumption. This has been termed "carnivore attrition" or "carnivore ravaging" in the North American literature.
3. *Transport* of bones individually or in body segments away from the acquisition locale, with their accumulation in other locales (burrows, caves, cliffs, trees).

These three types of carnivore effects parallel those of humans, who modify bones during killing, dismemberment, and nutrient extraction, destroy some elements or segments of elements while processing them, and selectively transport body segments to other locales. Humans also directly modify bones with their teeth, as will be outlined in this chapter. Understanding the key differences – or sometimes the lack of them – between nonhuman carnivore and human effects on bone is thus important to assemblage analyses in regions inhabited by larger carnivores as well as hominins.

In early works on taphonomy, carnivore impacts were seen as a major "bias" affecting bones as they moved from life context to fossil context. Modification and deletion of skeletal elements or segments by carnivores is undeniable, but it is more useful to focus on the evidence *added* by such processors (Chap. 3). Tooth marks and other traces of carnivore action on bone are "trace fossils" (Bishop 1975), reflecting ecological relations between species. Likewise, carnivore bone accumulations do not just represent deletion of prey animals' bones from where they died: these specimens offer information on predator behavior in ancient landscapes. If context and other taphonomic modifications indicate that humans originally generated an assemblage that carnivores then modified, this reveals interactions of at least three species – prey animals, humans, and carnivores. To paraphrase Andrew Sillen (1989:228) again, carnivore bone modification is not the "mist on the window" into the past, but is instead part of the view.

12.1.1 Environment, Ecology, and Behavior: Relation to Carnivore Bone Processing

There is no such thing as a typical carnivore, even among terrestrial mammals. Canids, felids, hyenids, ursids, mustelids, herpestids (mongooses and relatives), and Australian marsupial carnivores differ in their predatory and feeding adaptations and thus in their impacts on skeletal elements. Modern studies also indicate that mammalian carnivore species are extraordinarily flexible in their behavior as they respond to local and regional ecological variability. Prey species choice, killing methods, and carcass handling can vary substantially within one species. This especially applies to the extent to which predators consume bone. Actualistic research has shown that behaviorally flexible carnivores respond to changes in local conditions by changing their transport and consumption behavior, which in turn influences the osseous record of their activities. Kruuk (1972) and Blumenschine (1989) report demographically driven behavioral variability for spotted hyenas of the Serengeti-Ngorongoro region of northern Tanzania. In Ngorongoro Crater, where spotted hyenas were densest, they hunted in packs, engaged in hostile interactions with other hyena groups, and tried to drive lions from their kills. In other areas, spotted hyenas were fewer, lived in small social groups, and obtained more food by non-confrontational scavenging. In a detailed 40-year analysis, Faith and Behrensmeyer (2006) document a major decrease in carcass and element frequencies in the Amboseli National Park landscape as a lion-dominant ecosystem, with an abundance of drought deaths, was supplanted over three decades by a hyena-dominant carnivore community with some lions, cheetahs, and jackals.

It follows that, to evaluate carnivores' role in modifying an archaeofaunal sample, it is essential to have some grasp of the carnivore community extant when and where the assemblage formed (Delaney-Rivera et al. 2009). If hominins lived in animal communities with high numbers of wild carnivore species and considerable competition, bone consumption and transport effects may be stronger than among the same species under less densely packed conditions (Gidna et al. 2013). Likewise, unprovisioned scavenger dogs in human settlements, as opposed to well cared for working dogs or pampered pets, may attack bones differently. Such knowledge, if at all possible to obtain, permits a more discerning view of carnivore modifications in an archaeofaunal sample. To gain a sense of carnivore community structure and possible levels of motivation to move and consume bones, zooarchaeologists studying recent archaeofaunas can use historic records or data from prior archaeological analyses. At deeper time depths, assessing carnivore communities and their effects on carnivore bone modification is more challenging but zooarchaeological analyses demonstrate it is not impossible. Paleontological reports permit assessment of predatory adaptations and as well as the functional anatomy and locomotor and feeding patterns of extinct carnivores (e.g. Delaney-Rivera et al. 2009; Van Valkenburgh 1988). Marean (1989) assessed the role of saber-toothed machairodont cats in the Olduvai paleocommunity, arguing that analogies with modern carnivore communities neglects the unique scavenging opportunities these predators may have offered hominins. Stiner (1994) began her analysis of Italian Middle Palaeolithic archaeofaunas from caves by reviewing carnivore taxa documented in earlier research, then assessing modern conspecifics' or close relatives' cave use and effects on bone.

Although zooarchaeologists' and taphonomists' observations of wild and captive animal were intended to elucidate bone modification, they have also clarified the roles of carnivore feeding strategies and of bones in ecosystems (Blumenschine 1989; Blumenschine et al. 1994; Haynes 1980b). As such, they have bridged between biological approaches to animals in landscapes and zooarchaeological and paleontological analysis.

12.1.2 *Relation of Consumer Size to Size of Affected Carcass or Bone*

The bone modifications described in this chapter reflect circumstances that leave some residual bone for zooarchaeological analysis. Just as the morphology of breakage to fresh bone is to an extent governed by the relation between the force an actor can apply and the level of force an element can withstand (Chap. 11), so, too, bones' survival varies according to a similar interaction of size relations. When a wolf captures a lemming, it makes short work of eating the entire animal. The action of the wolf's strong jaws and stomach acids reduce the lemming's bones to small fragments or completely destroy them. The same wolf feeding on an adult deer or caribou handles the carcass according to a sequence that maximizes recovery of nutritious tissue while minimizing energy expenditure and risk of injury while dealing with a body larger than its own. This case will leave more skeletal remains, some maybe scattered or transported, some bearing traces of the wolf's feeding behavior. If the same wolf were to acquire a bison carcass, it would follow similar cost-benefit strategies as in handling deer or caribou, but with relatively diminished ability to disarticulate body segments or to consume bones, perhaps resulting in a less dispersed skeleton.

12.1.3 Carnivore "Ravaging:" A Plea for a More Objective Terminology

Before turning to carnivore modifications to bones, I want to argue for a more objective descriptive terminology. Following Binford (1981; Binford and Bertram 1977), several influential North American zooarchaeologists (e.g. Lyman 1987; Marean and Spencer 1991) have adopted the phrase "carnivore ravaging" to describe destruction of bones and bone segments by nonhuman meat consumers. By "ravaging," Binford meant the typical patterns of carnivore destruction of bones. This is an unfortunate term because of its common connotations and its implicit decoupling of carnivore effects on bone from their ecological context. The verb "to ravage" means to pillage, ruin, annihilate, destroy, ransack, lay waste to, devastate, or plunder (Merriam-Webster.com 2008), sometimes used metaphorically, as in "the ravages of time."

Calling what carnivores do to bone as an integral part of their behavioral ecology "ravaging" is both inaccurate and parochial. Though Binford probably never intended to divorce carnivore impacts on bones from their ecological contexts, "ravaging," suggests an unproductively anthropocentric approach. It implies that carnivore action is the "mist on the windscreen" of archaeofaunal analysis, to use Sillen's terms again, rather than "part of the view." Less pejorative phrases, such as, "carnivore bone reduction," or "carnivore processing," could be used with equal ease and greater scientific and biological precision. Given the use of "handling time" in behavioral ecology, "carnivore handling" is another alternative.

12.2 Carcass Consumption Sequences

According to their overall size in relation to the animal consumed and to their dentitions, mammalian carnivores differ in the degree of damage they can inflict on bone. Nonetheless, they tend to feed on bodies of larger animals in a generally similar order, and likewise, those that obtain nutrients from within bones gnaw elements in a similar sequence. Such consumption sequences have been documented by Binford

(1981), Blumenschine (1986), Brain (1981), Haynes (1980b), and others. Carcass and bone consumption sequences reflect a kind of "optimal foraging" on carcass parts, with the zones offering the highest nutrients yield for the energy spent, plus lowest risks of injury to teeth and mouth, consumed first. The carcass consumption sequence begins with viscera and muscle, moves to large muscles, finally to segments with less muscle mass or those with musculoskeletal attachments that present more challenges. Handling skeletal elements, a bone-consumer begins with the most nutritionally rewarding and least physically challenging skeletal elements or element portions, leaving the less rewarding and more challenging for later, if at all. The carcass consumption sequence is described by Haynes (1980b) and Blumenschine (1986) as follows:

1. Anal region, belly, and internal organs.
2. Hindquarters: rump and upper hind leg.
3. Back ribs, including cartilage.
4. Forequarters: shoulder and upper foreleg.
5. Head and neck muscle.
6. Lower limb bones.

According to the condition of consumer and prey and levels of intra- and interspecific competition for nutrients, a carnivore will go through part or all of this sequence before abandoning the carcass.

12.2.1 Bone Reduction by Canids and Hyenids

Bone-consuming carnivores also display generally similar patterns in bone consumption, according to the type and density of the bone tissue (Binford 1981; Binford and Bertram 1977; Brain 1981; Marean et al. 1992). This sequence is as follows:

1. Least dense and most porous bones, cartilaginous ends and then bones of ribs, vertebrae, scapulae, innominates, and other bones.
2. Slightly more dense cancellous epiphyses of long bones.
3. Denser compact bone elements enclosing edible soft tissues.

The same factors as influenced carcass consumption will affect how thoroughly a carnivore pursues this sequence.

12.3 Carnivore Effects on Skeletal Elements and Segments

Living carnivores that can most intensively modify skeletal elements are members of the zoological families Canidae (dogs and foxes) and Hyaenidae (hyena species). Canids and hyenid long bone consumption is outlined by body segment below (Binford 1981; Binford and Bertram 1977; Haynes 1980a, b).

12.3.1 Skull

As large and relatively thick-walled bone units, crania present a major challenge to potential consumers. Crania that fit into a consumer's jaws can be punctured or collapsed by static loading. Blumenschine (1986) and others noted that larger ungulate crania are left more or less intact in the Serengeti ecosystem, even after hyena feeding. If carnivores can accomplish any cranial reduction, it is usually through the facial region. Horwitz and Smith (1988) note that striped hyenas habitually removed facial bones from human crania dug from graves, and that some were reduced to fragments. In ethnoarchaeological site surveys along northeastern Lake Turkana shorelines, I encountered two adult human crania that had all ethmoid, sphenoid, and basicranial bone removed and hyena-size tooth marks near the break margins. Variations in the motivation of hyenas to break down braincases may reflect ecologically based differences in food availability: the low productivity environments of the Negev and Lake Turkana offered fewer opportunities to obtain protein and fat-rich tissues such as offered by the brain (Stiner 1994), and hyenas may risk tooth damage to obtain them in these situations versus the higher productivity Serengeti (Van Valkenburgh et al. 1990).

In ungulate species and in humans, mandibles readily detach from the cranium (Chap. 19). Roots of mammal teeth are embedded in a blood- and fat-rich tissue, called "pulp" in dentistry, within the dentary bone. Grazers and browsers with high-crowned teeth that erupt over years have deeper dentaries and more pulp. Carnivores gnaw the angle of the mandible or the underside of the dentary to open the pulp cavity. This leaves the dental row intact and may not damage the ascending ramus (Binford 1981).

12.3.2 Vertebrae

Vertebrae are some of the more delicate elements in the skeleton, being substantially reduced by consumers of sizes smaller than the prey animal and completely destroyed by consumers of equal or larger body sizes. Captive hyenas consumed nearly 100% of sheep vertebrae in captive feeding trials (Marean and Spencer 1991; Marean et al. 1992). Similar results were reported by Binford et al. (1988) monitoring wild hyena bone processing of equal and slightly larger animals. Brain (1981) reports that cheetahs, not habitual bone consumers, nonetheless reduce vertebral segments of baboons and small gazelles, as can leopards observed in captive feeding trials. Transverse and spinous processes of vertebrae often display gnawing marks resulting from attempts to remove the attached muscle tissues. The relatively dense zygapophyses, the small articular facets on the fore and aft of each vertebral arch, may remain.

12.3.3 Ribs

Ribs contain red marrow and are attractive to carnivores. They also serve as anchors for complexly layered thoracic and abdominal muscles, and their proximal ends underlie the muscle groups running longitudinally down the spine. Consumers may damage ribs as they feed on those muscles. Carnivores normally reduce ribs attaching to the sternum via a cartilage link from the sternal end, or, if floating ribs, from the ends terminating in cartilage. Heads of ribs may be chewed if dislocated or disarticulated from thoracic vertebrae.

12.3.4 Shoulder and Pelvic Girdle

Blades of scapulae and innominates, with cartilage plates at their extremities and multiple muscular attachments, are usually gnawed inward from their zones of cartilage and muscle attachments. Areas typically displaying tooth marks are the vertebral border of the scapula, and in the innominates, the ischial tuberosity, the iliac crest, and sometimes the pubic symphysis (see Binford 1981: Fig. 3.36).

12.3.5 Long Bones

Trabecular tissues of the least dense epiphyseal ends of the bone are consumed first, using incisors, canines, and tongue to gouge and scoop out cancellous tissue, producing a cylinder of the compact diaphyseal bone. The carnivore attempts to collapse the cylinder by compressing it at more or less right angles between its carnassial teeth (upper P4 and lower M1). If the cylinder does not collapse, the actor orients it in parallel to its carnassial teeth and presses down to puncture the shaft, repeating the action to open a “channel” in parallel to the long axis of the bone, driving off chips of bone in the process. Canids may stabilize the shaft between their front paws while doing this. Once the cylinder is sufficiently weakened by channeling, the actor collapses it by compression and gains access to the marrow in the endosteal cavity, leaving long, channeled, and flaked splinters.

Binford (1981:51) described another kind of long bone reduction, “chipping back,” a variant of channeling, in that the bone is held in the same orientation and carnassials are applied. The teeth may be placed against a ridge or process on the cylinder, and the carnassials pressing on the cortical bone remove small flakes in a kind of pressure flaking. Bone fragments and small, dense bones may be swallowed whole and subject to stomach acids. In canids, undissolved fragments pass through digestive track and are excreted in the feces. Hyenas vomit bone not fully digested.

12.3.6 Carpals, Tarsals, Metapodials, and Phalanges

In ungulates, the metacarpals and metatarsals are long bones, and they are treated as such by non-human carnivores: gnawed at epiphyses, especially the less dense distal ends, and diaphyses collapsed for yellow marrow within the diaphysis. Toe bones are often nibbled away for the marrow they contain and the fat in their cushion pad. If carnivores carry prey limbs away from the acquisition site, carpals and tarsals may "ride" with the more nutritionally rewarding long bones with which they are tightly articulated (Binford 1978; 1981, see Chaps. 18 and 19). Hyenas are reported to swallow, digest, and/or regurgitate dense bones of the carpal and tarsal joints (Marean 1991).

12.4 Characteristic Marks of Carnivore Processing

Carnivore marks inflicted on bones are made by teeth, by polishing with the tongue, or by stomach acids, after bone fragments have been ingested. These typical marks were first studied in canids, and then the effects of spotted hyenas were documented. Key works include Binford (1962, 1981), Haynes (1980a, 1983), Shipman and Rose (1983), and a critical comparative review by Lyman (1987).

12.4.1 Tooth Marks and Other Carnivore Modifications

Tooth marks on vertebrate remains make more sense if the apparatus that inflicts these traces is understood. Figure 12.1 shows a wolf skull as a representative of placental mammalian carnivore dentitions. It is heterodont, possessing more than one tooth shape. In mammals, incisors and canines seize the prey during acquisition, rip off soft tissue, and are used to crush and scoop out cancellous bone. Anterior premolars and carnassials chop up soft tissues before they are swallowed and also compress and break down denser compact bone cylinders. Because carnivores break bone cylinders by squeezing it in their jaws' vise-like grip, a general principle is that each tooth mark on the intact circumference of a long bone should have an opposing mark. If the bone broke into two or more pieces during or subsequent to infliction of the marks, opposing marks may be missing. However, when the actor producing the marks initially appears ambiguous, searching for opposing marks can help narrow the range of possible actors. Because carnivore teeth are heterodont, upper and lower teeth may not be placed on the bone shaft at the same angle, and resulting opposing tooth marks may not have identical shapes or equal depths.

Tooth marks have been described as falling into several morphological types. The descriptions and terminology given below are based upon publications by Binford (1981:51–86; Binford and Bartram 1977), Blumenschine (e.g. 1995), Domínguez-Rodrigo and associates (Domínguez-Rodrigo and Barba 2006; Dominguez-Rodrigo and Piqueras 2003), Fisher (1995), Haynes (1980a, b, 1983), Shipman and Rose (1983),

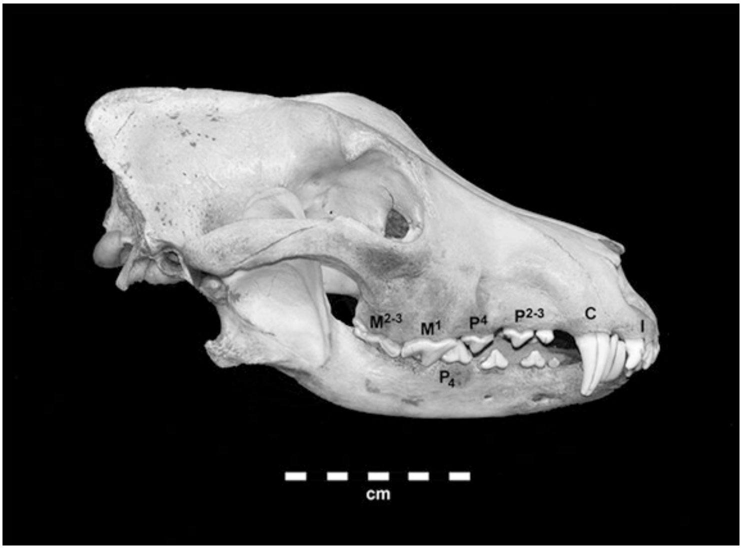

Fig. 12.1 A wolf cranium and mandible, showing the incisors (I), canine (C), anterior premolars (P2-3), carnassials (lower P4 and Upper M1), and posterior molars. While this dental arrangement differs from one zoological family to another in the precise numbers of teeth, it is generally similar in all placental carnivores and has strong parallels in marsupial carnivores. (Photo by the author)

and Delany-Rivera et al. (2009), as well my own experience with modified bones. These traits best describe bone surface modifications made by canids and hyenids.

1. *Tooth pits* are made on cortical bone by the anterior premolars or carnassials. They are relatively small marks, often triangular or diamond-shaped when seen from above (Fig. 12.2), but if made by individuals with worn and broken teeth, they may be rounder or irregular. They are often associated with tooth scores.
2. *Tooth scores* are grooves usually produced on cortical bone by anterior premolars or carnassials. They are made as a tooth cusp drags over the compact bone surface, from the pit initially made by the cusp on compression (Fig. 12.3). Longer scores usually curve slightly, and scores are U-shaped in cross-section compared to cut marks (Chap. 14). Scores may show downward crushing of bone into the groove and lack linear striations typical of stone tool cut marks (Fig. 12.4).
3. *Punctures* are holes punched through thin overlying cortical bone into cancellous tissue or into an underlying cavity. Punctures are usually made by canines or premolar cusps and are roughly oval or circular. They often display downward displacement of the cortical bone layer into the hole (Fig. 12.5).
4. *Flaking* of cortical bone, especially long bones, results from static loading homologous to lithic pressure flaking, as a carnivore grips compact bone between the cusps of two opposing teeth. If one such compressing cusp lies on an acutely angled edge of broken bone, the bone fails, driving off a flake from the outside of the bone into the endosteal cavity.

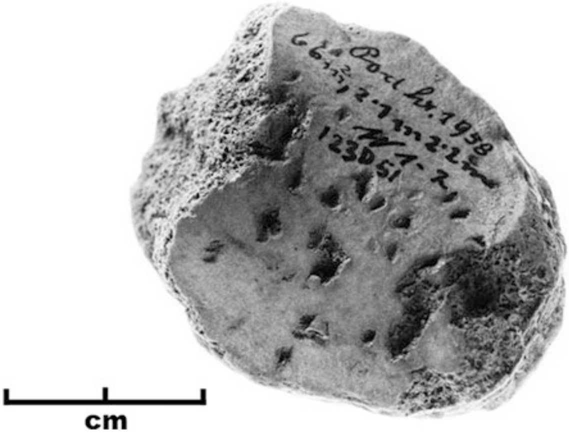

Fig. 12.2 Cave bear (*Ursus spelaeus*) patella from Pleistocene deposits in Pod Hradem Cave, Czech Republic, showing smaller, sub-triangular tooth punctures and furrowing from the edge of the articular surface. Tooth marks are within the size range of deciduous wolf (*Canis lupus*) teeth. Scale bar is 1 cm. (Photo by Robert H. Gargett (1996: Fig. 6.18), used with permission of author and University Press of America)

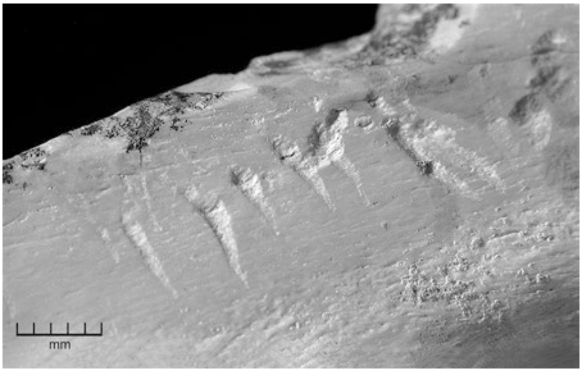

Fig. 12.3 Fossil bone surface from the Nihewan Basin, Hebei Province, People's Republic of China, showing the relation of the initial pit made by a tooth cusp to a score resulting from the tooth being dragged across the bone surface. (Photo by Don Harris of a specimen donated to the author by Dr. Wei Qi, 1989)

Fig. 12.4 Heavily dog-gnawed bovine bone (*Bos taurus*), showing tooth scores over the surfaces, with chipping-back and rounding of the distal end of the bone. (Photo by Don Harris of experimental specimen collected by the author)

Fig. 12.5 Bovine (*Bos taurus*) proximal femur from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya, showing hyena-sized carnivore tooth puncture on femoral head. (Photo by Don Harris of specimen collected by the author in September 1973)

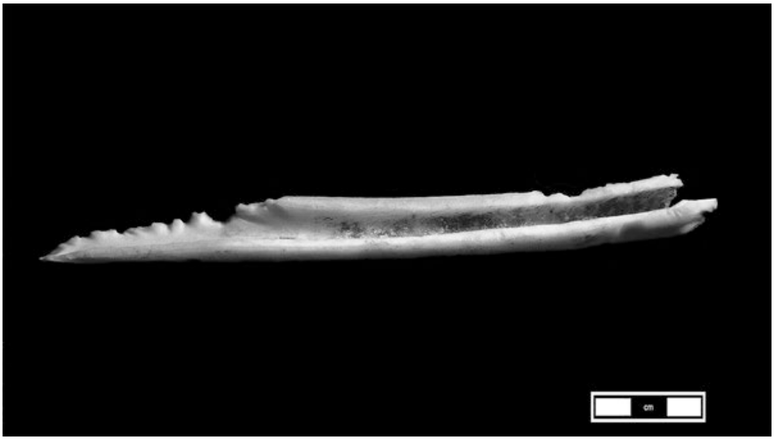

Fig. 12.6 Shaft fragment of a mule deer *(Odocoileus hemionus*) femur, showing crenulation by carnivore tooth action (tooth size in range of coyote, *Canis latrans*). Break surfaces and edges also display rounding and polishing resulting from licking. (Photo by Don Harris of a donated specimen from Stanislaus National Forest in the author's lab)

(a) If teeth are placed along a crack parallel to the long axis of a long bone, or along the edge of a flat bone such as a scapula, and if the compression is repeated, a continuous line of small flake scars may develop, forming a scalloped edge (Fig. 12.6). Binford called this *crenulation*. Flakes are normally neither stepped nor hinged and lack crushing at the point of percussion that is typical of human hammerstone impacts (Chap. 14).

(b) If the compact bone cylinder is clamped between teeth at an end, and a section is then levered upward with the actor's neck muscles, a flake scar oriented *parallel* to the long axis of the bone is driven off. Binford (1981:51–54) termed this *chipping-back* and stated these scars more commonly display stepping (Fig. 12.7).

Fig. 12.7 A bovine (*Bos taurus*) femur shaft fragment heavily gnawed by dogs, showing tooth scores over the surface, with chipping-back and rounding and polishing of the distal end of the bone. Greater light reflectance at left is due to the polishing action of the dog's tongue. (Photo by Don Harris of experimental specimen collected by the author)

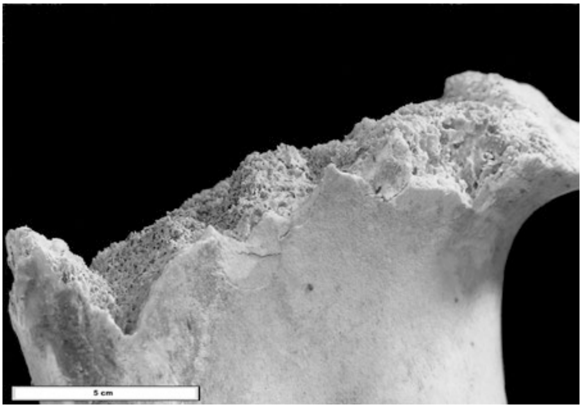

Fig. 12.8 Bovine (*Bos taurus*) proximal humerus from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya, showing hyena-sized carnivore tooth furrows on humeral head, with some compact bone depressed into the underlying cancellous tissue (Photo by Don Harris of specimen collected the author in September 1973)

5. *Furrowing* is damage to cancellous bone caused by repeated scraping of canines or premolars across the trabeculae, producing high and low rows, or furrows (Fig. 12.8). Furrowing results from reiterated gnawing similar to that producing crenulation in cortical bone but furrows develop gouges in trabecular bone instead.
6. *Scooping out* is the removal of cancellous bone from the spongey bone within a diaphysis at either end of a long bone. The actor pushes the drags incisors into the cancellous tissue and scrapes with the teeth, licking out the broken-down cancellous tissue. Canids using this technique can sometimes invade the marrow cavity (Fig. 12.9).
7. *Smoothing and rounding* is produced by repeated licking and grinding of a compact bone fracture surface by tongue and teeth. It may be mistaken for tool use or other abrasion (Figs. 12.6, 12.7, and 12.9).
8. *Lamellar and cortical bone loss, pitting, rounding, thinning of bone walls* is typical of stomach acid modifications and may be found either in vomited or defecated prey bones of carnivores, depending on the taxon. High frequencies of such bones in an area may reflect where carnivores have habitually defecated near dens or where dogs were confined (Fig. 12.10).

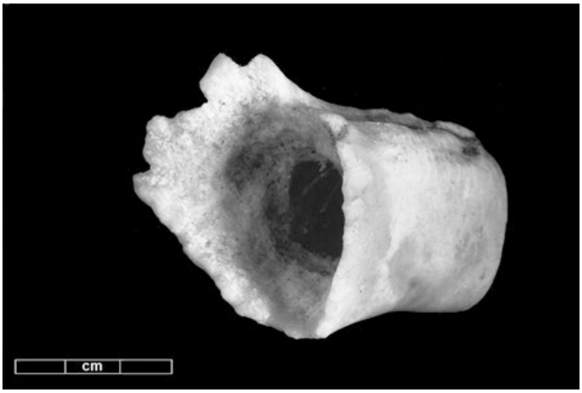

Fig. 12.9 The same heavily dog-gnawed bovine femur (*Bos taurus*) as in Fig. 11.4, showing scooping-out of the cancellous tissues at the distal end, plus chipping-back, rounding and polishing of the compact bone at the bone's distal end. Greater light reflectance is due to the polishing action of the dog's tongue. (Photo by Don Harris of experimental specimen collected by the author)

Large carnivores will reduce large animals' epiphyseal ends first. Only when driven by the need for lipids will most large carnivores other than spotted hyenas attempt to collapse diaphyses. Figures 12.4 and 12.7 show the unsuccessful efforts of Labrador retriever and German shepherd dogs to collapse limb shafts of cattle femora, despite much gnawing, and wolves appear to calibrate their efforts to bone sizes they can break without too much effort and risk (Binford 1981). A major difference between larger ungulate skeletal assemblages processed by large carnivores and those of the same sized prey processed by humans is in the reduction versus non-reduction of long bone epiphyses and other elements with lower densities of bone mineral. In the simplest case, assemblages processed by carnivores would be characterized by a lack of bones composed mainly of cancellous tissues, missing long bone epiphyses, the presence of diaphyseal cylinders, or collapsed fragments of them, and many fragments bearing some tooth marks. Samples produced exclusively by humans will preserve delicate elements and long bone epiphyses and display traces fragmentation by percussion to the shafts. Matters are not usually so straightforward in real life. Some assemblages of ancient bones show the effects of carnivores and of hominins, and much basic research has been aimed at clarifying such "multi-agent" assemblages, an area that will be discussed in more detail in Chap. 17.

12.5 Differing Effects of Carnivore Taxa: Surface Modifications and Bone Destruction

Although a general relationship exists in the amount of damage a consuming carnivore can cause based on its size relative to that of the consumed prey, different families of carnivores vary in their damage to bones. The following section summarizes the effects of members of major taxonomic groups.

12.5.1 Canids

Wild and domesticated dogs eat flesh, blood, and internal organs and gnaw bones to obtain nutrients in them. Canids have somewhat less knife-like molar teeth than do felids, and they can more readily gnaw bones without risking tooth breakage than can cats. Young wild canids more than adults gnaw bones as they develop their jaw muscles and erupt their adult teeth. Domestic dogs may gnaw bones more than do wild dogs, partly because they often depend on leavings from human meals, and partly because they may have been selected by humans to continue to show "infantile" behaviors into adulthood, such as being friendly, not overly predatory, etc. They may therefore be "stuck" at the gnawing stage of development that adult wild canids leave behind.

Canids favor cancellous bone of vertebrae, ends of long bones, the innominates, and ribs, to gain access to fat-rich neural tissues of the spinal cord and blood cells in the spongy bone, as well as to endosteal marrow in long bones. Canid feces may contain bone fragments displaying erosion from stomach acids (Fig. 12.10).

Wolves are the best-documented canid species that transporting bones of larger prey to lairs to nourish the young (Stiner 1991). However, recent studies of two South American fox species, *Dusicyon paeus* and *D. griseus*, have shown that some prey species' bones are also accumulated in their dens in rock shelters (Mondini 1995).

Fig. 12.10 Rodent mandible that has passed through the digestive system of a captive margay (*Leopardus wedeii*), showing loss of lamellar bone, thinning and rounding of bone walls. Each bar of dashed line in upper left is 1 micron. (Unpublished photo by Peter J. Andrews, used with his permission)

12.5.2 Felids

Extant cats such as lions, tigers, leopards, lynx, and smaller cats concentrate on flesh, blood, and internal organs and do not habitually gnaw bones to obtain nutrients. Large cats thus have lighter impacts on skeletal elements than do larger canids and hyenids. However, they do damage bone during the kill or in their attempts to detach limbs, usually using canines or carnassials (Figs. 12.11 and 12.12), and some may engage in further bone gnawing (see below). Canines of extinct and modern cats, and especially the saber-toothed cats, create distinctive scores resembling metal edge cuts in sharpness and asymmetrical angle (Fig. 12.13). Captive large cats are known to gnaw epiphyses of larger animals after they have stripped them of meat.

South American zooarchaeologists and taphonomists have established that pumas (*Puma concolor*), one of two large American cats, can gnaw bones and transport body segments to dens. In addition to marks illustrated in Figs. 12.11 and 12.12, pumas can inflict pitting, scoring, scooping-out, crenulation, and long bone fractures on prey bones as large as the guanaco (*Lama guanacoe*), which weigh 53–64 kg (Borrero et al. 2005). Mondini and Muñoz (2008) summarize findings from a variety of South American habitats and discuss ecological factors that may structure variations in pumas' bone-consuming behavior.

Based on their tooth form and postcranial anatomy, extinct saber-toothed cats such as *Smilodon, Dinofelis,* and *Homotherium* are now thought to have preyed on large, slow-moving prey. Increasing evidence exists for diversity in various species' handling of bone. Based on comparison tooth morphology and dental microwear in modern large cats and *Smilodon fatalis*, Van Valkenburgh et al. (1990) established

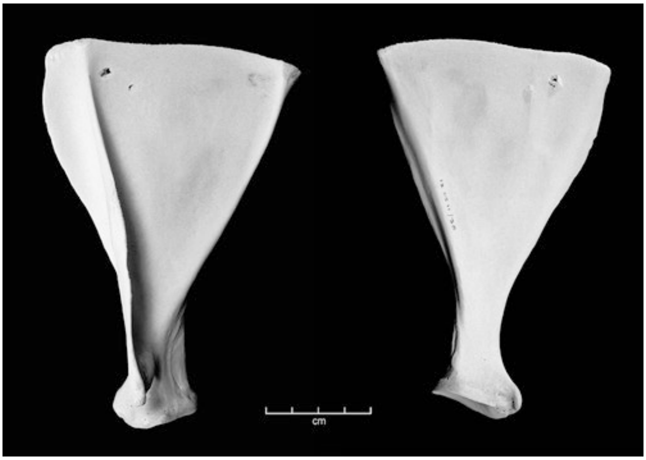

Fig. 12.11 Puncture marks made by the canine and premolar of a puma (*Puma concolor*) in a scapula of a female mule deer (*Odocoileus hemionus*), killed by a puma on the University of California, Santa Cruz campus. (Photo: Don Harris of bone in UCSC Anthropology Teaching Laboratories, UC Santa Cruz)

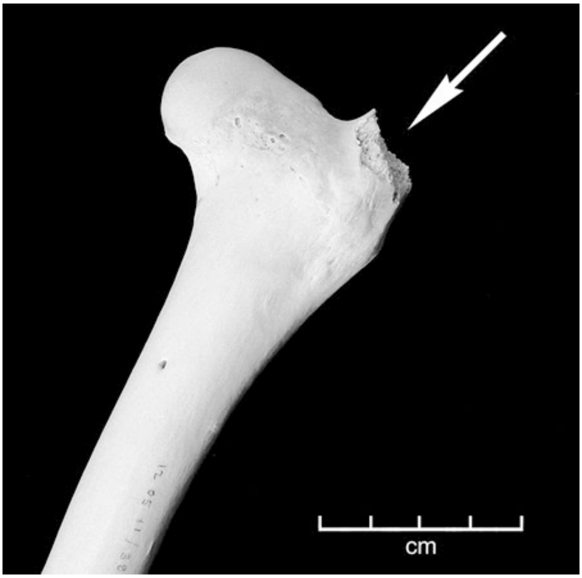

Fig. 12.12 Femur from same female mule deer (*Odocoileus hemionus*) killed by a puma as in Fig. 12.11, showing shearing across greater trochanter associated with detachment of the hind leg from the hip socket (*arrow*). Animal killed on the University of California, Santa Cruz campus. (Photo: Don Harris of bone collected by UCSC Anthropology Teaching Laboratories, UC Santa Cruz)

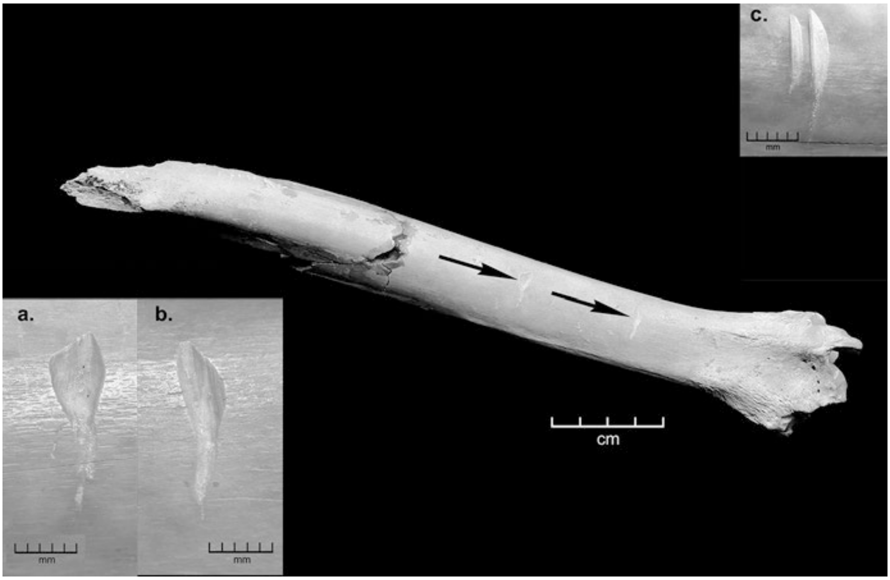

Fig. 12.13 Paired marks of the posterior surface of canines of *Homeotherium* sabertooth cat on tibia of a deer (*arrows*) from Nihewan Basin, Hebei Province, Peoples Republic of China. This probably resulted by a sabertooth catching the leg of a living deer in its jaws to capture it, rather than from consumption. (**a**) Close-up of the left mark; (**b**) Close up of right mark (*arrows*). (**c**) Paired tooth marks on other side of the tibia. (Photos by Don Harris of specimen courtesy Dr. Wei Qi, composite by the author)

that *Smilodon* probably had even less dental contact with bone than do cheetahs. Analyzing element frequencies and bone surface modifications of the paleontological archaeofauna from Friesenham Cave, Texas, Marean and Ehrhardt (1995) inferred that *Homeotherium* probably transported limbs of immature proboscidean prey to its lair, removing flesh with its serrated teeth. Prey species and body segment representation in South African australopithecine cave archaeofaunas diverge from what would be expected from that typical of Africa's only prey-transporting cat, the leopard, also suggesting diversity in ancient felid ecology (de Ruiter and Berger 2000; Pickering et al. 2004).

12.5.3 Hyenids

Four hyena species of Hyaenidae live in African and Asia today and formerly had broader ranges in Eurasia. Three have massive jaw muscles, stout, bone-cracking teeth with rounded cusps, and stomach acids capable of thoroughly dissolving bioapatite. The spotted hyena *(Crocuta crocuta*) can digest bones of animals up to rhinoceros size (Kruuk 1972). Spotted hyenas living in larger groups hunt socially, while solitary animals or those small groups emphasize scavenging. In areas with denser human populations, they scavenge human refuse and sometimes dig up burials. Such disparate foraging strategies are reflected in hyenas' effects on bones in the landscape, as carcasses rapidly disappear in high density areas but remain in lower density zones.

In habitats not heavily altered by humans, striped hyenas (*Hyaena hyaena*) hunt porcupines, rodents, and other smaller prey and scavenge larger animals, while scavenging refuse and human burials in heavily settled areas (Horwitz and Smith 1988; Kuhn et al. 2009; Lotan 2000; Monchot and Mashkour 2010). The brown hyena (*Parahyena brunnea*) was formerly widespread in southern Africa but is more sensitive to human habitat alterations than are spotted hyenas. Brown hyenas hunt small game, scavenge animals killed by other predators, hiding body segments under bushes, or transporting them to dens (Mills and Mills 1978). They can reduce the long bone ends of medium- to large-sized artiodactyls. Scott and Klein (1981) report a fossil brown hyena den, and Kuhn et al. (2009) report modern dens in the Rietvlei Nature Reserve, Namibia, as well as summarizing the literature on effects of three species.

Hyenas do not pass large bone fragments through their digestive tracts. They dissolve bone fragments into a calcium-rich "porridge" in their stomachs with extremely strong stomach acids and vomit out any larger fragments. Their feces are often pure white after drying because of the dissolved bone. Therefore, in contrast to feces of canids, hyena excrement should contain no bone fragments recognizable as such.

Marean, Blumenschine and coworkers (Marean and Spencer 1991; Marean et al. 1992) assessed the impacts of captive spotted hyenas, in experimental feeding trials with sheep-sized skeletal elements. They offered one and four hyenas, depending upon the trial, two types of bone samples. The first were intact bones stripped of most of their muscle and other external tissues but with all nutritional tissues in them, including yellow marrow. The second were intended to mimic elements processed by hominins, that is, not only stripped of meat but also broken open with hammerstones and marrow extracted. The latter was aimed at eliciting traits of so-called "dual-patterned" assemblages in which scavengers consumed hominin bone refuse. In the first set of experiments, hyenas consumed epiphyses, collapsed diaphyses, and consumed the yellow marrow in the endosteal cavity (Figs. 12.5 and 12.8). In the second, they consumed epiphyses but did not gnaw the diaphyses, as no marrow was to be gained by doing so. Researchers concluded that the presence or absence of mid-shaft carnivore tooth marks was a reasonable index of the order in which hominins and bone chewing carnivores had access to skeletal elements. Domínguez-Rodrigo and colleagues (Domínguez-Rodrigo 2003; Domínguez-Rodrigo and Barba 2006) critically assessed these arguments, and the controversy over the meaning of marks on Olduvai bones has continued (e.g. Blumenschine et al. 2007).

12.5.4 Ursids

Extant bear species vary considerably in their degree of carnivorousness. Ancient species' feeding habits should therefore be evaluated before assuming they hunted or scavenged. For example, stable isotopic analyses of European Pleistocene cave bears (*Ursus spelaeus*), combined with biomechanical analysis of their bones, indicates this species was primarily a vegetarian (Bocherens et al. 1990). Stiner et al.'s (1996) discussion of cave bears behavior in Yarimburgaze Cave, Turkey, noted that all living bear species avoid bringing carcasses or body segments to hibernation and birthing dens, with very rare exceptions. Gargett's (1996) research on the non-archaeological Pleistocene fauna from Pod Hradem Cave, Czech Republic, suggests that cave bears did not gnaw their own species' bones that accumulated through natural deaths in their hibernation dens. Most tooth marks on *Ursus spelaeus* bones from Yarimburgaze Cave and Pod Hradem were attributable to canids, probably wolves, and hyenids, probably spotted hyena, which inhabited Eurasia during most of the Pleistocene.

Haynes (1983) studied bone modifications by captive bears in zoos, including brown bears (*Ursus horribilis*) and marks inflicted on ungulate carcasses scavenged by wild black bears (*Ursus americanus*). Modern bears gnaw long bone ends, but even the largest bears do not inflict as much damage as do wolves on bones of comparable size. Ursid premolars and molars are low-crowned and broad, less suited to penetrating bone, and their marks on bone are shallow and cover a broader area in relation to depth, with furrowing common in cancellous tissue (Fig. 12.14).

Fig. 12.14 Bovine (*Bos*) femur gnawed by a captive brown bear (*Ursus arctos*), showing broad, shallow, furrowed surface of the modifications (Specimen courtesy Gary Haynes, photograph by the author)

12.5.5 Australian Marsupial Carnivores

Before the arrival of Europeans, the only placental carnivore in Australia was the dingo, a feral canid introduced there by aboriginal colonists. A numerous fossil and modern marsupial carnivore species existed on the continent. The best-documented recent marsupial bone collectors and modifiers are the eastern and western quolls, *Dasyurus geoffroii* and *D. viverrinus* (Leung 2002; Dela Cruz 2002), and the Tasmanian devil (*Sarcophilus harrisi*).

Quolls are small predators, weighing 0.85–1.3 kg, which consume insects, ground-nesting birds, and other small terrestrial or arboreal animals. They scavenge and transport parts of animals beyond their own competence to kill, including sheep, to their lairs (Fleay 1932). Based on experimental feeding trials, Walshe (1994) concluded that quolls are unlikely to leave distinctive marks on larger animals' bones.

Weighing 4–12 kg, Tasmanian devils have massive jaws and are superb scavengers and bone-crushers, capable of consuming all but the largest wombat and kangaroo bones (Guiler 1970; Marshall and Cosgrove 1990). The species was historically confined to Tasmania, but *Sarcophilus* remains are widespread in Holocene mainland Australian deposits. Tasmanian devils forage on the ground and in trees, taking reptiles, small marsupials, and nesting birds (Dewey et al. 2001). They habitually use dens but, unlike quolls, do not accumulate carcasses or bones in them. Feeding experiments by Sobbe (1990, cited in Walshe 1994) with captive Tasmanian devils documented scores, pits, furrows, and punctures paralleling those inflicted by placental carnivores. However, these marks were left on bones at feeding sites rather than in lairs. *Sarcophilus* pass bone fragments, occasionally complete feet of small prey, through their digestive systems, thus forming recognizable scat deposits (Marshall and Cosgrove 1990; Walshe 1994).

Walshe (1994:152–68) notes that carnivores much larger than *Sarcophilus* existed in Late Pleistocene and Holocene Australia, including the thylacine, *Thylacinus cynocephalus*, and marsupial tiger, *Thylacoleo*. Thylacine anatomy, and the behavior of the few observed before their historic extinction, suggests that their foraging and bone modifying behaviors may have been more like that of *Sarcophilus*.

12.5.6 Human Gnawing

Zooarchaeologists have been aware for some time that marks made by human teeth on bones can mimic those of carnivores (e.g. Solomon 1985; White 1992; Binford 1978, 1981; Gifford-Gonzalez 1989; Oliver 1993, 1994). Four actualistic studies, two experimental and two ethnoarchaeological, have clarified these matters considerably. Elkin and Mondini (1996) conducted experimental feeding of identical sets of sheep axial and appendicular bones to humans and Pampa foxes, *Pseudalopex gynnocercus* (4.5–6.5 kg). More bones in the human experiment were marked gnawing than were bones the fox experiment, but one axial set was apparently completely consumed by the foxes. Both samples included scoring and pits on cortical bone and punctures on cancellous tissues, as well as removal of the ends of bones.

Fernández-Jalvo and Andrews (2011) combined experimental chewing of sheep and pork ribs by 18 modern Europeans with the examination of sheep bone specimens collected by C. K. Brain in the 1960s from Koi people at Zoutrivier Village, Gobabeb, Namibia (Brain 1981). Bringing together these data with a review of the literature up to that time, they listed eight morphological traits of bones chewed by humans (Fernández-Jalvo and Andrews 2011:121, Table 2):

1. *Bent ends* (fraying)
2. *Curved shape* at the terminations of thin bones
3. *Crenulated edges*
4. *Double arch punctures* on broken edges
5. Triangular, dispersed, and rare *puncture marks* on bone surfaces
6. Shallow, transverse, or oblique *linear ma*rks on bone surface
7. Shallow *surface scratches* associated with shallow crescent pits made by incisors

These modifications are generally distinctive from those made by nonhuman mammalian carnivores, although some overlap with chimpanzee-modified bone specimens. Landt (2007) further clarified human bone modification and its similarities with modifications by carnivores, using bones collected from Bofi foragers in the N'gotto Forest of the Central African Republic. As others, he noted the pits, scores, punctures, as well as notches, crenulated edges, and crushed or fractured edges, the latter sometimes called "mashed" edges in earlier literature (e.g. Binford 1978; Fig. 11.16). This last is probably the most diagnostic of human modifications relative to carnivore marks, produced by alternately chewing epiphyses or bone segments with premolars and molars and sucking fat and marrow from the crushed tissues. During ethnoarchaeological fieldwork with the Dassanetch people of northeastern Lake Turkana in the 1970s (Gifford-Gonzalez 1989), I collected such specimens (Fig. 12.16) after sheep and goat feasts in my camp. Similar human tooth mark modifications were reported by Martínez (2009) on monkey bones in his ethnoarchaeological study of hunting and animal processing by the Nukak people of the Columbian Amazon.

Landt introduced useful distinctions, including that the extent of human tooth marking of bone varied with the size of the prey. Bones of smaller prey such as pouched rat and porcupine showed larger human tooth marks than did those of blue duiker, a small forest antelope or very small murid mice, which he relates to their mode of consumption (Landt 2007:133, 137). Landt (2007:1637) stresses that, "not only are human tooth marks on small animals likely to be confused with those of small canids on similarly sized remains, but the size of the mastication damaged prey is an important variable that needs to be controlled in future research." This message is reinforced by Martínez (2009) and by Delany-Rivera et al. (2009), whose research included experimental human gnawing effects on bovine ribs (see *Can Tooth Marks Distinguish Carnivore Taxa or Size?* below).

As might be expected, chimpanzees and baboons produce similar mastication marks on bone to those made by humans, so in contexts where other primates might be present, diagnosis should always involve contextual evidence (Pickering and Wallis 1997; Plummer and Stanford 2000; Delaney-Rivera et al. 2009; Dominguez-Rodrigo and Piqueras 2003). However, for zooarchaeologists working with later archaeofaunas in other areas the criteria outlined above may help sort human impacts from those of smaller carnivores (but see *Can Tooth Marks Distinguish Carnivore Taxa or Size?* below).

To sum up, some human tooth marks resemble some carnivore tooth marks, especially those of such small canids as foxes, jackals, or smaller dogs (Fig. 12.15). Presence of several of Fernández-Jalvo and Andrews's eight human dental modifications, as well as a *lack* of other typically carnivore modifications in an

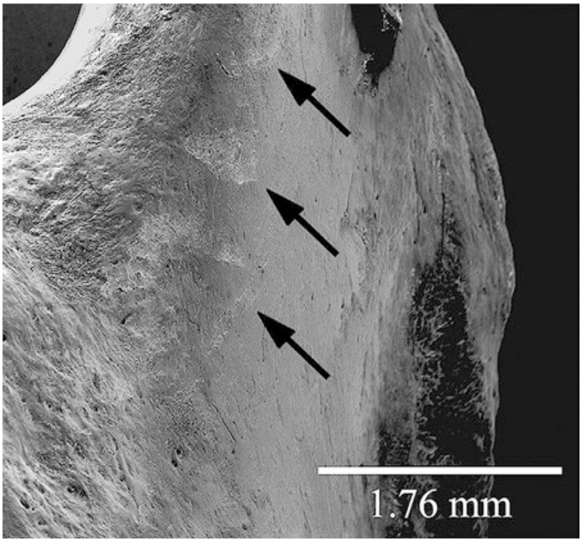

Fig. 12.15 SEM image of irregular human tooth pits on the pubic ramus of a giant pouched rat. (Micrograph from Landt (2007:1635, Fig. 3) of ethnoarchaeological bone sample, used with the permission of the author and Elsevier)

Fig. 12.16 Adult caprine radius and metatarsal, showing tool-aided fracturing distally and crushing damage by human mastication to proximal ends, from Dassanetch ethnoarchaeological bone sample collected by author. (Photo by author)

assemblage, increases the likelihood that human actors were responsible for the damage. Other forms of contextual evidence, such as cut or chop marks and spatial setting, may also serve to clarify the likely agent(s) (Fig. 12.16).

12.6 Crocodylian Effects on Bone

Crocodiles and their relatives inhabit tropical and subtropical waters around the world. Some exclusively eat fishes, while others actively prey on terrestrial vertebrates and scavenge carcasses from lake or river margins. In the process, they may leave tooth marks on bones. Larger crocodilians take live prey fording rivers, wading into water to drink or forage, and in some spectacular cases, may lunge on to land to seize an animal standing near the water's edge (Njau and Blumenschine 2006). Two sets of researchers have conducted captive feeding experiments with Nile crocodiles (*Crocodylus niloticus*), using medium (1.5–2.0 m) to large (>4 m) animals (Njau and Blumenschine 2006; Baquedano et al. 2012). Njau and Blumenschine also collected ungulate bones from the banks of the Grumeti River, where crocodiles take zebra, wildebeest, and other prey during the yearly migrations to the Serengeti Plains.

Njau and Blumenschine concluded that marks made by crocodylian teeth overlap those made by mammalian predators, but that a few distinctive differences existed. Crocodiles do not gnaw bones and only occasionally fracture them with the pressure of their jaws. Their tooth marks are most common on limbs, and the authors report a high rate of marks, plus two distinctively crocodylian marks. The first the authors called a "bisected pit," in cortical and cancellous bone (Njau and Blumenschine

2006: Figs. 2, 3, and 4). At eruption, crocodylian teeth possess a ridge, or carination, on the mesial and distal edges of each tooth, which produces the distinctive bisected signature. The second were relatively rare j- or u-shaped "hooked scores" (Njau and Blumenschine 2006: Fig. 6). These are inflicted during the so-called "death roll," crocodiles' unique method of breaking up a carcass: one or more predators clamp down on a limb and forcefully roll in the water, producing such marks as bone moves against the teeth. Baquedano et al. (2012:1731–32) also noted microstriations along tooth scores (Fig. 5).

Based upon their respective studies, Njau and Blumenschine (2006) and Baquedano et al. (2012) coincided on the following points (Baquedano et al. 2012:1732):

1. Crocodile-created assemblages are composed of primarily complete elements, with minimal fragmentation.
2. These elements exhibit absence of gross gnawing.
3. Crocodile-generated bone assemblages lack disarticulation of complete skeletal units, with the potential of abandoning a large portion of articulated specimens.

Baquedano et al. (2012) disagreed with Njau and Blumenschine that bisected – what they call carinated – tooth marks have a morphology never documented in marks produced by mammalian carnivores, noting that some terrestrial mammal carnivores such as lions have similar canine morphology. They also noted much lower rates of tooth marks on bones, a difference could stem from the two teams' differing experimental contexts. Njau and Blumenschine's (2006) feeding trials involved many animals actively competing for the food items, while the other, captive animal experiment seldom had more than one large, dominant animal feeding, with others sneaking parts but not actively competing. Baquedano et al. (2012) speculate that lack of a free-for-all in their experiment could account for this disparity. They did not observe "hooked scores," which they note may be a sample size effect, since these were rare (<0.01%) in Njau and Blumenschine's sample of 2000 elements, compared to their 198. Persons working with archaeofaunas in which alligator or crocodile impacts are a possibility are referred to these well-illustrated works.

12.7 Can Tooth Marks Distinguish Carnivore Taxa or Size?

Whether one can distinguish carnivore species using tooth marks on bone specimens has been debated by taphonomists and paleoanthropological zooarchaeologists (Delaney-Rivera et al. 2009; Domínguez-Rodrigo and Barba 2006; Selvaggio 1994; Selvaggio and Wilder 2001; Fernández-Jalvo and Andrews 2016), with most opining that this is not possible. Delany-Rivera et al.[1] reviewed the literature, and concluded this is not possible, for reasons that can be summarized as follows:

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[1] Delany-Rivera et al. (2009) also describe a quick and non-destructive method of measuring tooth marks other markings on bone with digital camera and open source software.

1. Tooth pits of various mammalian carnivores and omnivores are not taxonomically diagnostic.
2. A weak relationship exists between the body size of the processing carnivore and tooth mark size, but considerable overlap exists between marks made by different-sized processors.
    - (a) Marks on diaphyses are not reliable indicators of the size of the consumer. Marks on epiphyses and metaphyses are more reliable indicators.
3. Some such overlap is explained by consistent inter-taxonomic differences among the tooth impacts of bone-gnawing species.
    - (a) Marks made by smaller canids and other medium sized processors overlap with those made by large felids.
    - (b) Baboons and humans leave a very wide range of tooth marks on bone, overlapping those made by hyenas and lions in size and shape, as well as those of smaller bone gnawers.

When attempting to infer the body mass of bone modifying carnivores, tooth mark dimensions should be used in conjunction with patterns of destruction and modification of skeletal elements of different sizes, which may reflect the maximum jaw gapes of the modifiers (see *Relation of Consumer Size and Size of Affected Carcass or Bone*).

12.8 Carnivore Carcass Dismemberment and Transport

Carnivores often acquire animal bodies some distance from where they prefer to consume them. Prey that are small relative to the predator are transported whole to preferred locations. Larger animal bodies dismembered during the kill or initial consumption may be carried in segments from the acquisition site. Some species' repeated actions in transporting body segments build up substantial accumulations of bones in one locale. Carnivores' selective transport and accumulation parallel those of humans and will be treated in more detail in Chap. 19.

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Chapter 13
Avian Carnivore, Ungulate, and Effects on Bone

This chapter reviews the effects of other vertebrate actors that can affect archaeofaunal assemblages. In contrast to Lyman's (1994b) review of taphonomy, it does not attempt a treatment of all aspects of these actors' effects but rather focuses on those aspects of their behavior most likely to impact archaeofaunal assemblages. It begins with avian carnivores, enumerating their bone damaging and reducing abilities, most common bone surface modifications, roles as bone accumulators, and potential for paleoenvironmental information. It then reviews similar traits of herbivores, both hoofed animals and rodents, emphasizing what motivates these taxa to modify or accumulate bones.

13.1 Avian Effects on Bone

Birds that modify bones include the avian raptors: hawks, falcons, eagles, buzzards, vultures, owls, plus tropical taxa such as bustards and other terrestrially adapted birds of prey. The most frequently consumed raptor prey are microfauna, defined by Andrews (1990) as mammals, birds, reptiles, and amphibians less than 5 kg in body weight. Within this, common prey species are rodents and insectivores; eagles may regularly take lagomorphs and the young of larger mammal species. Vultures and other avian scavengers often consume carcasses of much larger animals.

Archaeologists seeking to tease out human subsistence practices in such areas as arid North American West knew that ethnographic accounts testified to an overlap in prey taken by humans and by raptors, especially rabbits, hares, and larger rodents. Remains of such animals in caves and rock shelters where raptors may have roosted, even when spatially associated with artifacts, present a problem: were these the debris of human meals, or of raptors that occupied the same space, either sequentially or simultaneously? Practically speaking, can human consumption of these prey species be distinguished from that of raptors, from bone surface modifications

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or skeletal element representation? These questions guided much actualistic research into raptor effects on vertebrate remains by zooarchaeologists.

Likewise, paleontologists long recognized the potential of predatory birds' microfaunal accumulations for reconstructing paleoenvironments. The central question was whether raptor-accumulated microfaunal samples reflect an essentially random sample of microfaunal taxa around a raptor roost, or are they more idiosyncratic, species- or individual-specific, and hence less representative of paleoenvironments? Even earlier than did zooarchaeologists, paleontologists turned to actualistic research to explore this question.

Systematic taphonomic studies of avian effects on the remains of vertebrate prey or scavenged animals developed to answer both these questions. Detailed studies now indicate the distinctive impacts avian carnivores have on prey bones. This section summarizes the relevant literature on avian modifications to bone and on avian sampling of microfauna, with an eye toward these two issues.

Avian raptors cause three kinds of alteration to skeletal elements of vertebrate bodies they consume:

1. Bone surface modifications inflicted by the beak or by the talons during killing and eating. Damage reflects breaching the braincase and tearing body segments and flesh with beaks, as well as gripping prey during the kill and feeding with talons.
2. Destruction of skeletal elements or parts of them by stomach acids, the degree of destruction varying with taxon, owls being less likely to completely dissolve bones than are falcons, hawks, eagles, and vultures.
3. Transport of skeletal elements from the acquisition site to roosts or nests for further consumption or provisioning the young, accumulating bone debris at those places.

As with mammals, the extent of damage to bones results from interaction of the consumer's strength (usually correlated with body size) relative to the strength of the bones of the consumed (again, usually correlated with body size). Raptors can exert extraordinary levels of force relative to body weight, as some examples will show.

13.1.1 Consumption-Related Bone Breakage and Destruction

Owls usually hunt in the early morning, late evening, or night. Their prey are usually small relative to their own body size, and owls tend to swallow them whole, or to detach the head and then swallow the head and the postcranial body as two units (Andrews 1990). They later vomit up bones and bone fragments embedded in fur or feather pellets, which shield their digestive tracts from injury. Owls generally inflict less breakage on postcranial elements during consumption than do other raptors, though Andrews (1990:51) reports that certain owl species may produce considerable damage to elements. In most cases, they breach the braincase, as they usually kill prey by a bite to the back of the skull, and consume the brain early in feeding.

Even within one well-studied owl species, variability exists in the degree of bone damage. Saavedra and Simonetti (1998) compared three Chilean barn owl (*Tyto alba*) samples with five North American barn owl samples documented by others. They noted differing element frequencies and degrees of fragmentation across all samples and found significant divergences between the Chilean and North American samples, as well as within the South American samples. Kusmer (1990) offered a comparative discussion of taphonomic processes affecting prey remains consumed by owls. She cautions that, although owls usually inflict less damage than do other raptors, size matters. Smaller owl species and the young of larger species tear off parts of the body before swallowing, in the process breaking skeletal elements of prey more than do larger owls, who can swallow them whole. De Cupere et al. (2009) reported differences in processing depending upon whether female owls are rearing unfledged young, when the mother dismembers prey to a greater degree to feed her chicks than she would feeding herself. This produces greater degrees of skeletal damage in nesting sites assemblages than at roosts.

Diurnal raptors such as eagles, hawks, and falcons often take prey closer to their own body size, which require handling before consumption. These raptors break down bodies into segments and tear flesh from bones before swallowing them. Like owls, they regurgitate undigested parts in pellets. While diurnal raptors break cranial and postcranial elements more often than owls, their fragmentation rates seldom approach those of mammalian carnivores processing similar vertebrates (Andrews 1990:50–58). Avian raptor pellets have a different morphology in fossil form than do small mammal scats, and their bony contents tend to be considerably more complete (Andrews 1990:28; Mellet 1974); Schmitt and Juell (1994); (Schmitt 1995).

Andrews (1990) reviewed actualistic data on avian and mammalian carnivore modifications to microfauna, and Bochenski (2005) discusses actualistic findings on imperial eagle, golden eagle, tawny owl, eagle owl, long-eared owl, peregrine, and gyrfalcon prey element frequencies and modifications, specifying the rates of accumulation of axial versus limb elements, wing versus leg, amounts of digestion, etc., with useful tables. Lyman (1994a).

Eagles regularly take rabbits and hares, which are also human prey. Archaeological researchers on foragers in the Great Basin, USA have elucidated differences in assemblages produced by these actors. Hockett (1991, 1993) compared leporid remains from hawk, eagle, and owl roosts with those from archaeological sites. He reported that in eagle roost assemblages, crania, mandibles, humeri, and tibiae were present in relatively high frequencies, as Andrews (1990:51) found. Hockett's (1993) eagle roost analysis revealed feeding-related damage on leporid femora and tibiae; the large muscles attached to these elements may encourage more intensive handling. Hockett (1993) also reported that eagles produced diaphyseal cylinders on leporid tibiae similar to those found in archaeological sites, but that the eagle-processed cylinders were generally longer than those from human meals. However, he cautioned that raptor-processed tibiae resembled the first step in Great Basin foragers' bone bead production: removal of epiphyses via transverse fractures. He advocated further comparative work to sort out consistent indicators of one actor or the other. Schmitt (1995) examined leporid bones at two golden eagle (*Aquila chrysaetos*) roosts in the Great Basin, comparing element frequencies to Hockett's barn owl samples and to coyote scats. He found that hind limb elements were the commonest bones in the eagle samples, significantly diverging from patterns of representation in other avian and mammalian carnivores. He suggested eagles' handling of hind limbs conserves the elements in identifiable form, whereas consumption by coyotes does not.

13.1.2 Effects of Beaks and Talons

Hawks and eagles can inflict surface modifications on the bones of very small to medium sized animals. Lagomorphs have been the focus of special interest because of the use of rabbits and hares by raptors and humans. Several researchers have attempted to specify distinctive signatures of talons and beaks. Punctures to the cranium, probably associated with the killing bite, and to the innominates, associated with seizing and pinning the prey during the kill, are reported. Beaks also inflict notches along the margins of flat or previously broken bones. Hockett (1993:672) noted that avian punctures and notches lack opposing marks, unlike mammal tooth marks (Chap. 12). Andrews (1990) and Schmitt (1995:248) note that fractures produced by raptors were not associated with distinctive surface modifications. All three authors reported that punctures were relatively rare on mammalian prey. Bochenski et al. (2009) report considerable puncture damage inflicted during consumption by two European eagle species on the bones of large avian prey (Fig. 13.1). Such differences may reflect avian bones' greater delicacy and divergences in bird from mammal anatomy.

Berger and colleagues (Berger and Clarke 1995; Berger and McGraw 2007), analyzed modifications to fauna associated with the *Australopithecus africanus* juvenile from Taung, South Africa, and inferred avian involvement in the accumulation. Three species of modern African eagles regularly take antelopes up to 30 kg, the young of larger primates, and, very occasionally, small human children. Berger and colleagues studied fossils collected from a modern South Africa black eagle (*Aquila verreauxii*) nest, documenting taxa taken, element frequencies, and modifications. Assessing the non-hominin fossil sample recovered from the Taung deposits, they reported depressed fractures, punctures, notches, and scratches on small to medium vertebrates similar to those made by contemporary eagles (Fig. 13.2). These, the ubiquity of species taken by modern eagles, presence of very large eggshell fragments, and overall physical situation led investigators to infer that the Taung sample represents a large eagle nest. Berger and McGraw (2007) argue that the *Australopithecus* specimen itself displays punctures and scratching around the orbits similar to that on monkeys eaten by eagles and should also be considered eagle prey. While not disputing some raptor involvement at Taung, de Ruiter et al. (2010), question association of the Taung *Australopithecus* with other fossils recovered from an active lime works operation, as well as whether modifications on the specimen were perimortem.

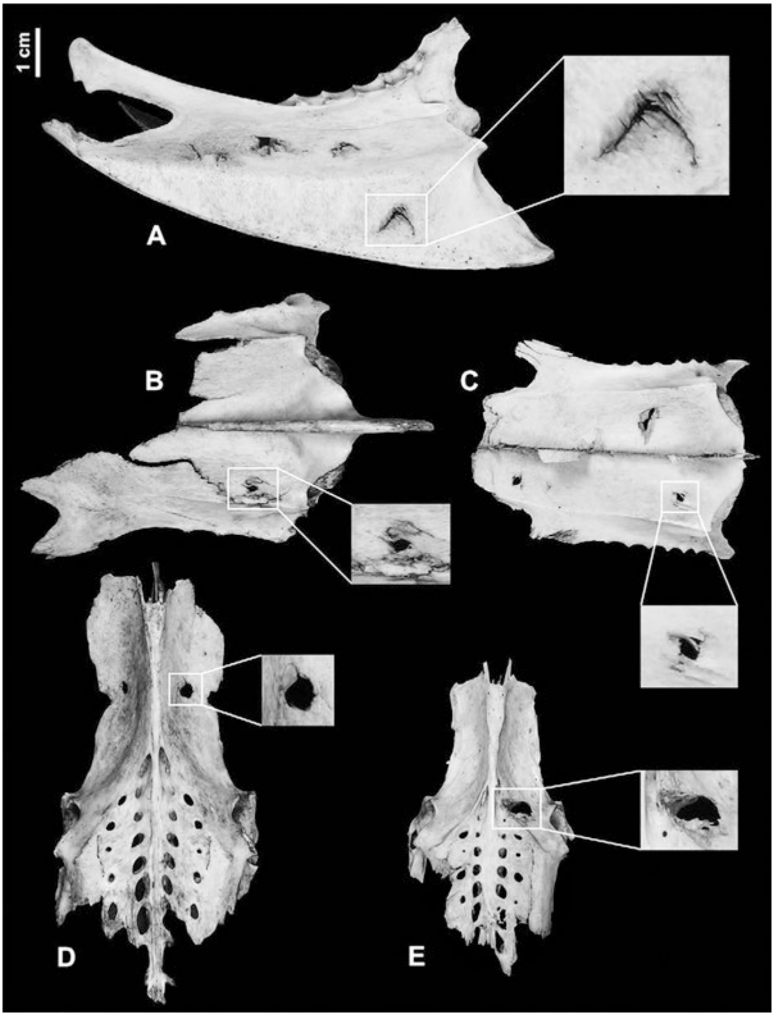

Fig. 13.1 Puncture marks made by white-tailed eagles on sternal and pelvic elements of large avian prey: **A.** nearly complete sternum of a meganser duck, with holes in corpus and crista sterni; **B.** anterior part of sternum of a meganser duck with a hole on the left side of body; **C.** nearly complete sternum of a duck, with several holes in body; **D.** pelvis of a goose, with holes in both preacetabular wings of each ilium; **E.** pelvis of a goose, with a hole above antitrochanter. (From Bochenski et al. (2009):126, Fig. 3, used with permission of the authors and Elsevier)

13.1.3 Raptor Stomach Acid Effects

Various taxonomic groups of raptors vary in stomach acidity levels, influencing their respective effects on swallowed bone. Acidity interacts with the size relations of predator to prey discussed above, and how commonly a species swallows whole

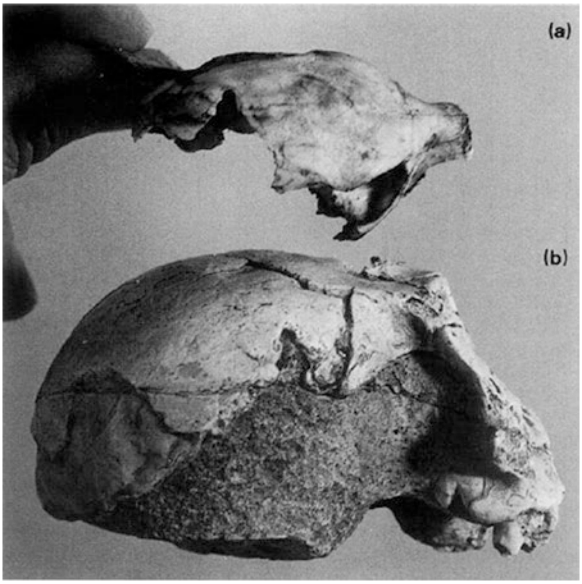

Fig. 13.2 V-shaped notches in the broken margin of (**a**) a modern hyrax cranium from a black eagle (*Aquila verreauxii*) nest and (**b**) a fossil baboon cranium from the Taung deposit. Notches are typical of beak punctures made along the edge of a skeletal element or on the edge of a break (From Berger and Clarke (1995):296, Fig. 12a and b, used with permission of the authors and Elsevier)

prey or skeletal elements. Owls have the least acid stomach environments, with pH 2.2–2.5, As a result, skeletal elements are best preserved in their pellets. Diurnal raptor stomach acids have pH of 1.2–1.8 (Andrews 1990; Dodson and Wexler 1979; Duke et al. 1976). For comparison, in giraffes and five other wild ruminant species, average pH in the abomasum section of the stomach is 3.6 (Bredin et al. 2008). Hawks' and eagles' regurgitated pellets contain fewer bones, and those present display more extreme pitting, erosion, and other acid-induced surface features than do bones regurgitated by owls (Mayhew 1977; Yalden and Yalden 1985). Nonetheless, captive owls have been shown to completely digest bones of some micromammals (Andrews 1990; Raczynski and Ruprecht 1974).

Vultures have extraordinarily high concentrations of stomach-acid producing cells and can dissolve larger bones, benefiting from the grease and collagen digested from bone. Houston and Copsey (1994) argued that, when carcasses are scarce, a bone diet may yield a higher caloric content than an equivalent weight of soft tissue. Margalida (2008:188) reported the bearded vulture (*Gypaetus barbatus*), weighing 4–6 kg, is the only vertebrate with a bone-dominated diet, consuming bones up to 28 cm by 4 cm. Its stomach acids can dissolve sheep-sized bones. Bearded vultures fracture bones by carrying them aloft and dropping them, and they stockpile bones at their nests for later consumption. Margalida (2008) demonstrated that these birds preferentially transport elements higher in white bone grease (oleic acid) content to their nests.

Skeletal elements with high surface-area-to-volume ratios, such as scapulae, innominates, and vertebrae, are most vulnerable to destruction by avian stomach acids, even by owls (Dodson and Wexler 1979; Andrews 1990). Actualistic research shows that acids consistently destroy carpals, tarsals, metapodials, and phalanges

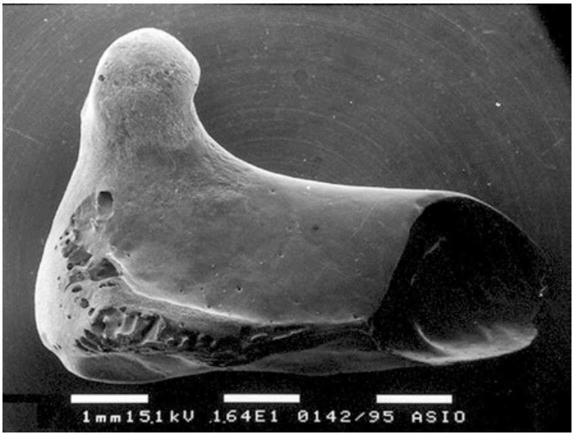

Fig. 13.3 SEM micrograph of acid-etched owl (*Asio*) femur, showing loss of cortical bone from trochanteric area and thinning of diaphyseal walls (Unpublished micrograph by Zbigniew M. Bochenski, used with permission of Z. Bochenski)

(Andrews 1990). The femur and tibia survive in relatively high frequencies. Maxillary and dentary regions of the skull, usually with their cheekteeth, are commonly preserved. Incisors and molars are among the last elements digested.

Bones that do survive to be regurgitated often display pits and fissuring etched by stomach acid, thinning or loss of cortical bone from epiphyses, thinning of diaphyses, and rounding of natural features and fracture surfaces (Fig. 13.3). Andrews (1990) illustrated the range of modifications typical of avian digestion, as did Fernández-Jalvo and Andrews (2016). Bochenski and Tomek (1997) discussed stomach acid erosion and delineate differences between this and bone surface erosion caused by soil pH.

Broughton et al. (2006) provided a case of barn owl (*Tyto alba*) predation on the tui chub (*Gila bicolor*), a fish species common in lakes of the North American Great Basin. They used a modern barn owl accumulation of fish bone from eastern Nevada as a dataset with which to compare a Terminal Pleistocene archaeofauna with the same species from Homestead Cave, Utah. They considered other actors in the Homestead Cave possibly responsible for the fish bone accumulation in their comparison, analyzing fish bone from modern coyote feces and that retrieved from human coprolites in Homestead Cave, also using notes on human digestive effects on fish bone (Butler and Schroeder 1998). Broughton et al. established that the Homestead Cave sample was in nearly all ways identical to the prey size parameters, element frequencies, and bone modifications of the barn owl fish bone sample and differed from actualistic samples of other actors. For Europe, Russ (2010) used comparative analyses of modern eagle owl pellets to assess whether this large raptor, known to accumulate bones of mammal prey in caves, would likely have accumulated fish bone as well. Although it is still possible some eagle owls accumulate fish bone, most modern samples yielded low frequencies of ichthyofaunal specimens. The author noted that further research is necessary.

13.1.4 Patterns of Raptorial Bone Accumulation

Raptors differ from mammalian carnivores in how they deposit bones of their prey. Pellets accumulate beneath habitual roosts, gradually releasing the bones as they dissociate and decay (Terry 2004). Andrews (1990:7–10) observed that raptors might trample older pellets and reduce delicate elements to fragments. Those that feed on larger prey and dismember and consume soft tissues often drop stripped bones below their roosts. Margalida's (2008) analysis of bearded vulture accumulations was noted above. Plug (1978), Mundy and Ledger (1976), and Richardson et al. (1986) studied bones around African vulture nests. These often bore traces of mammalian carnivore gnawing and were apparently scavenged from mammal kills by the vultures to provision their young. Richardson et al. (1986) reported that some such bones displayed acid alteration, reflecting on-site regurgitation by the vulturess.

Several researchers have assessed whether element frequencies or fracture rates alone can diagnose raptor agency and generally have found considerable diversity, even within species (e.g. Bochenski et al. 2009; Saavedra and Simonetti 1998). Commenting on the use of either element or fracture frequencies in diagnosing owls as agents, Kusmer (1990:636) stated:

> Although quantitative data may help to provide a short list of possible depositional agents, it may sometimes be more useful to approach the analysis from the angle of diagnostic marks (such as digestive erosion patterns) on individual bones and teeth. As always, multiple sources of evidence, including contextual and geological information, should be examined in conjunction… and form an important part of the taphonomic analysis of fossil assemblages.

Her generalization could well apply to all attempts to diagnose avian agency from fracture or element frequencies.

Terry (2007) revisited the question of determining the accumulating actor employing, principal component and discriminant function analyses on published micromammal datasets from raptor pellets (nocturnal and diurnal) and carnivore scats. She established that element fragmentation rates and the preservation of delicate versus sturdy elements could reliably distinguish nocturnal raptors (owl) samples from those produced by diurnal raptors and mammalian carnivores. However, diurnal raptors and mammalian carnivores could not reliably be distinguished one another by these or any other variables. Applying these actualistically-derived criteria to Grayson's (1998, 2000; see also Grayson 2011) data from the 12,000-year sequence at Homestead Cave, Utah, Terry (2007) established that owls were probably the dominant accumulators of microfauna throughout the Homestead sequence. She argued that this consistency in accumulating agents allows greater confidence in inferences about climate change from the shifts in micromammal species over time. The next sections discuss using raptor accumulations to infer paleoenvironment.

13.1.5 Raptors and Environmental Sampling

Earlier actualistic studies compared the diversity of microfaunal taxa trapped in a region with those represented in regional raptor pellets, concluding that raptor prey are *not* representative of a local community. Andrews (1990:28–29) discussed why this may be the case. First, some prey species are diurnal and others nocturnal, as are predator species; depending upon whether any given bones are accumulated by a diurnal or nocturnal raptor, one part of the circadian cycle will be sampled and the other neglected. Second, raptor species have prey size preferences, and species falling outside these ranges will seldom appear in their pellets. Third, through learned predatory behaviors, individual birds may develop even narrower prey species preferences. Andrews (1990:29) concluded that, although trapping-based species abundance and diversity data correlate well with general environmental type (e.g. high- versus low-productivity), it would be incautious to use data derived from raptor pellets to diagnose environmental type.

Other research supported these assertions. Hoffman (1988) notes that predatory behavior of some raptors may produce species structures entirely different from those in the environment. Brain (1981) compared species in modern barn owl pellets accumulating around two South African fossil localities with microfaunal taxa trapped in the two locales. He found that owls in the two areas diverged in species taken, and that neither prey profile was representative of the actual microfaunal community in their areas. Grayson (1981) and Andrews (1990) suggested treating pellet evidence as “presence or absence” data, rather than attempting statistical analyses of taxonomic abundance or diversity. In sum, the actualistic research suggested that, in the short term, no contemporary raptor samples of microfauna provides a representative sample of an environment’s microfauna, due to species- and even individual-specific prey selectivity.

However, paleontological and archaeological samples “compile” on a different temporal scale than is captured even by decades-long sampling programs. Acknowledging the limitations of actualistic-scale observations, Terry (2008) used modeling to explore whether the time averaging typical of paleontological assemblages might “smooth” such variability and produce taxonomic profiles that more accurately reflected community structure, and how much time such smoothing would require. Terry’s simplified model incorporated empirically derived data on multiple rodent species abundance cycles, which vary in frequencies and amplitude, and predator-prey interactions through such cycles. Terry’s (2008) results indicated that time averaging can smooth the swings in individual prey species abundances. A conservative estimate of the elapsed time needed to produce consistent taxonomic abundance estimates approaching those of the model life assemblage was around 140 years. Terry noted that this time span is roughly equivalent to that of the finest-grained time resolution of paleontological deposits. Thus, to use raptor accumulations for paleoenvironmental reconstructions effectively requires a more sophisticated approach, to overcome the “short attention spans” of actualistic studies although the longer-term of these contemporary studies may supply valuable information on frequency and amplitude of abundance cycles.

13.2 Ungulate Effects on Bones

Plant-eating vertebrates include the hoofed herbivores, or ungulates, and many rodent species. Both ungulates and rodents can modify and in some cases accumulate bones. Hoofed animals should further be divided between ruminant artiodactyls, a highly diverse taxonomic group with ruminating stomachs, and suids (pigs), artiodactyls with less specialized guts and in nearly all species a more omnivorous diet. Ruminants display great variability in crown heights but a common "plan" of interlocking premolars and molars with exposed enamel and dentine ridges on their occlusal surfaces that grate up leafy forage (Chap. 7). With a few African exceptions, pig species have omnivore diets and cheekteeth with rounded cusps. As a result of these differences, these two groups of artiodactyls mark bones differently and will be treated in separate sections below.

13.2.1 Ruminant Osteophagia

In environments poor in phosphorus, calcium, or sodium, each a necessary nutrient and bone component, ruminants often chew bones and antlers they encounter in the landscape to obtain these and other nutrients. Fresh or dry bones may be gnawed. Such bone recycling is called osteophagia, or pica. Osteophagia can completely destroy bones, or it can modify bone surfaces in ways that could be mistaken for carnivore gnawing or even human tool production. It has been documented from the early twentieth century from Africa (Theiler et al. 1924; Yellen 1977; Sekulic and Estes 1977), Europe (Sutcliffe 1976; Brothwell 1976; Kierdorf 1993), Arabia, and North America Sutcliffe (1973; Bowyer 1983) in camels, cattle, sheep, red deer/wapiti, giraffes, and various African antelopes.

Denton et al. (1986) explored the biochemical motivations of osteophagia through controlled experiments with heifers that had never before eaten bone, by lowering their blood serum phosphate levels and presenting them with bones along with similarly sized materials. With lowered blood serum phosphorus levels, the heifers quickly selected bones for chewing, apparently using olfactory cues, and engaged in "avid" chewing. They only stopped their gnawing a few hours after their blood phosphorus levels were returned to normal.

How ruminants absorb phosphorous from bits of masticated bone is unclear because of the ruminant digestive system's complexity. Forage passes from mouth to the reticulum to the rumen, where symbiotic bacteria ferment it. Then, it is regurgitated to be chewed again, then swallowed and further fermented in the rumen before passing to the omasum and finally to the abomasum, or true stomach, the only environment with acid-producing cells maintaining a low enough pH to dissolve bioapatite. Bredin et al. (2008) investigated the process of absorption, and readers seeking more information can consult that article. These authors note that saliva "softened" and produced "visible erosion" of cancellous bone, and opined

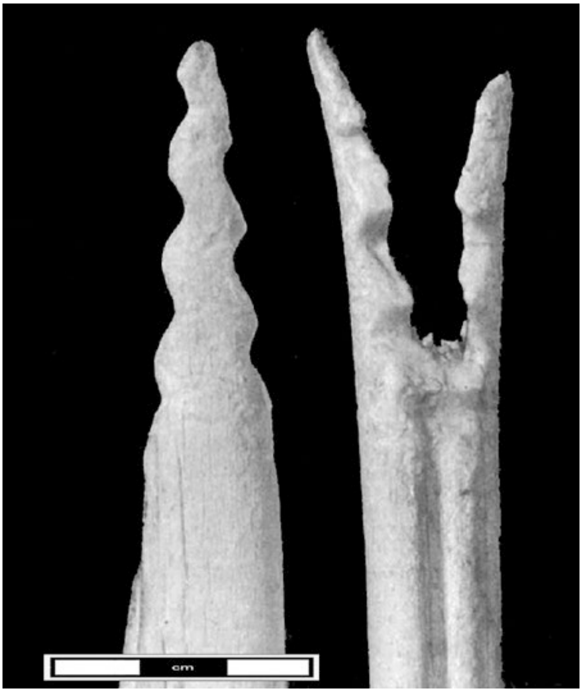

Fig. 13.4 Bones chewed by reindeer/caribou, showing the distinctive zigzag pattern of bone modifications produced by chewing the bones with the cheek teeth (From Sutcliffe 1973:Figs. 3 and 9, used with permission of Springer Publishing)

that saliva's effects may facilitate further mechanical breakdown of bone particles during rumination Bredin et al. (2008: 5–6).

Zooarchaeologists may encounter a range of osteophagia products. Sutcliffe (1973, 1976) described the process of dental modification by ruminants: they clamp bones between their premolars and molars in one side of the mouth, "like a cigar" (1973:429). Grinding their teeth against a length of bone scrapes bits of bone off the surface, leaving scars on opposing sides. With enough repetition, these actions produce zigzag profiles in gnawed long bones that, in their most extreme form, appear as "forks" or "prongs" on bone (Fig. 13.4). Brothwell (1976) noted that, depending on the original shape of the element, early stages of gnawing produce broad, flat marks, also reported and illustrated by Hutson et al. (2013) for skeletal elements chewed by giraffes and African antelopes. Both Hutson et al. (2013) and Cáceres et al. (2011) report and illustrate tooth scores oriented at right angles to the long axis of diaphyses (Figs. 13.5 and 13.6). Some modified diaphyses display what Hutson et al. (2013: Fig. 3) characterize as crushing or gouging. Both Hutson et al. (2013) and Cáceres et al. (2011) also report epiphyseal gnawing, leading to exposure of cancellous bone and its reduction into the "fork" shape with continued chewing, producing the pronged shape illustrated by Sutcliffe (Figs. 13.6).

Cáceres et al. (2011: Table 3) compared ruminant bone modifications to those of small to medium carnivores, and Hutson et al. (2013: Table 1) updated this for ruminant vs. large carnivore gnawing effects, using the same format. Both sets of researchers note that overlaps exists between herbivore and carnivore marks, but

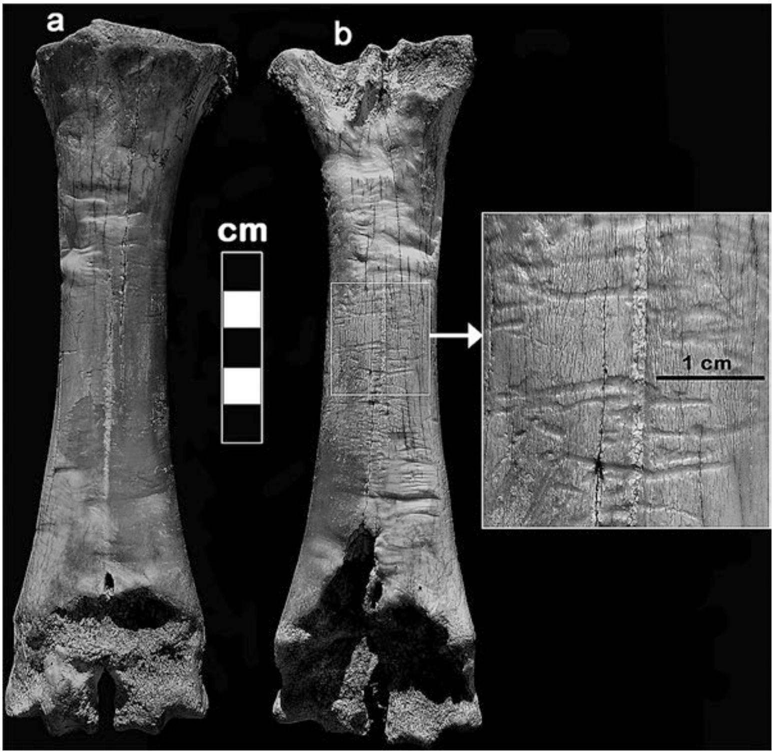

Fig. 13.5 Right ungulate-gnawed metacarpal of a bovid size class III (84–296 kg) antelope, from Kyle Recreational Park, Zimbabwe: **a** anterior view; **b** posterior view. Showing both horizontal scores to diaphysis made by cheekteeth and reduction of epiphyses (From Hutson et al. (2013):4142, Fig. 2. Used with permission of the authors and Elsevier)

some traits help sort out actor. Ruminants and carnivores both produce grooves and a form of scooping-out, but ruminants do not usually inflict pits or punctures along with these traces, nor does their scooping-out involve furrowing. Hutson et al. (2013: Fig. 9) illustrate comparative cases of giraffe, captive hyena, and wolf gnawing effects on the same element, a proximal tibia. These show carnivores' greater extent of compact and cancellous bone reduction (chipping back, scooping out).

13.2.2 Suid Gnawing of Bone

Most pigs are omnivores. Anecdotal reports of various wild species scavenging dead primates in brushy or forested environments, suggest they can completely consume the bones of small to medium-large animals (Galdikas 1978; Teleki 1973). Greenfield (1988) experimentally fed cattle and pig bones to domestic pigs. The pigs trampled bones to detach soft tissues, then gnawed smaller elements, and

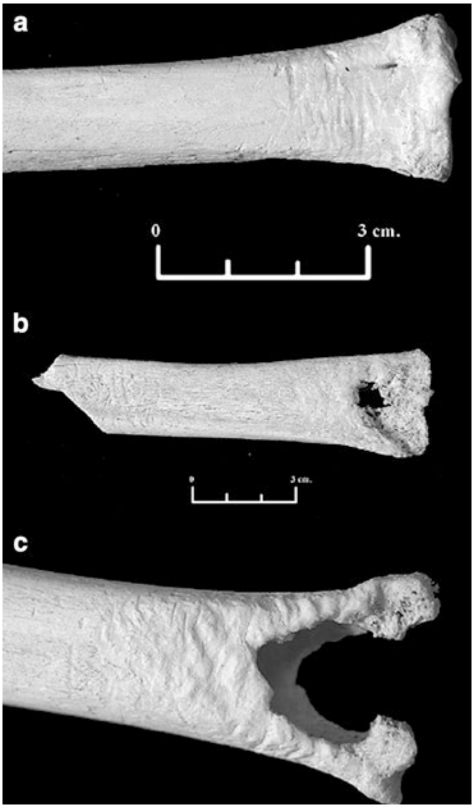

Fig. 13.6 Modification stages of herbivore-chewed bones. **a** Stage 1, transverse grooves inflicted on the proximal epiphysis. **b** Stage 2 (intermediate), cancellous bone is exposed and the epiphysis has started to disappear. **c** Stage 3, typical fork shape related to herbivore damage (From Cáceres et al. (2011):2769, Fig. 3, used with permission of the authors and Elsevier)

finally moved to long bones ends, showing disinterest in older, dry bones. They completely consumed suid bones and vertebrae of all sizes, while reducing but not destroying cattle long bones. Greenfield (1988:477) illustrated pig tooth marks on long bone epiphyses, reporting that some bones bore pits and others showed marks of the pigs' broad, shovel-like incisors.

Domínguez-Solera and Domínguez-Rodrigo (2009) did further experimental research on suid bone modification, feeding individual skeletal elements and carcass sections to free-ranging domestic Iberian pigs and wild boars (*Sus scrofa scrofa*). They laid out both unmodified bones and "dual-patterned" assemblages of long bones broken with hammerstones and the marrow removed (Chap. 12). Their findings supplement those of Greenfield in important ways:

1. Suids can destroy vertebrae and long bone epiphyses of sheep- and pig-sized animals and fragment their diaphyses. They modify cattle-sized bones, especially epiphyses.
2. Suids leave pits, scores, and furrowing on bone surfaces, but these modifications are inflicted primarily by their broad, flat incisors rather than by the cheek teeth and are generally shallower than those of canids.

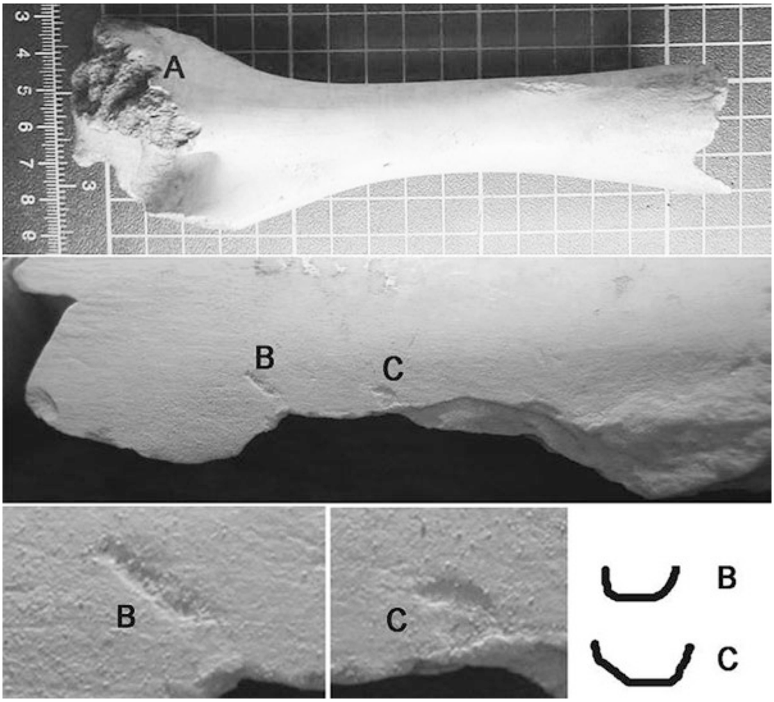

Fig. 13.7 **A.** Furrowing inflicted on epiphysis by pigs, showing the shallow and broad scars produced by incisors in cancellous tissues and **B., C.** tooth scores on compact bone (Domínguez-Solera and Domínguez-Rodrigo 2009:356, Fig. 9, used with permission of the authors and Elsevier)

3. In nearly half the experiments, tarsal bones of sheep- and pig-sized animals were consumed.
4. Unlike hyenas, pigs mouthed and licked diaphyseal shafts from which marrow had been removed, apparently seeking the last bits of adhering fat. In the process, they inflicted a considerable number of mid-shaft tooth marks (Fig. 13.7).

Zooarchaeologists working with archaeofaunas containing wild or domestic pigs should consider that scored, pitted, and furrowed specimens from larger animals could have been modified by suids rather than by true carnivores, attending closely to distinctive traits of the respective consumers' effects.

13.2.3 Ungulate Trampling

Hoofed animals can modify or break skeletal elements by treading on them. Skeletal elements are most likely to be damaged by trampling in high-traffic areas such as habitually used trails or waterhole margins (Behrensmeyer et al. 1989). If a

Fig. 13.8 Typical “wishbone fracture” behind mandibular symphysis on right dentary of a topi (*Damaliscus lunatus*), average body weight 118 kg. Death plus 2 years, Weathering Stage 2-3. East Lake Turkana, Kenya. Swiss Army Knife for scale is c. 5.7 cm (2.25 in) long. (Photo by the author)

substrate is of loose, sand- and gravel-size grains, treadage can deposit bones into the matrix, as it can in a moist, fine-grained matrix. If a fine-grained substrate is dry and hard, trampling can break the same elements. Types of damage produced by trampling include:

1. Fracture: some break forms, such as “wishbone” fractures of mandibles (Fig. 13.8), snapping in place to scapula blades, holes in weathered crania, etc., are characteristic of trampling. Others mimic breakage by other actors: spiral fractures, collapse of weathered long bone shafts, etc. (Figs. 13.9 and 13.10). Very large animals can crush entire elements (Fig. 13.11).
2. Polish: against finer substrates abrasion of bone surfaces appears as polished bone surfaces. Behrensmeyer et al. (1989) experimentally produced polishing in bones on game trails. Polishing may alter a patch of natural bone surface, a break surface, or a projection of an element (Fig. 15.5 shows an example of trampling abrasion).
3. Trample marks (“pseudo-cut marks”): V-shaped gouges with striated marks, resembling cut marks (Chap. 14) are usually developed on sand or gravel substrates. Shipman and Rose (1984) stated that “shouldering” effects may distinguish true cut marks from these marks. Lyman (1987) suggested that true cut marks should make anatomical sense in terms of disarticulation, defleshing, etc., and that trample marks are more randomly placed on convex bone surfaces. The next section reviews pseudo-cut marks in more detail.

Fig. 13.9 Collapse of a topi (*Damaliscus lunatus*) metacarpal along deep weathering cracks, in a disturbed area used by male topis for sparring during rutting season. Death plus 2 years, Weathering Stage 3. Swiss Army Knife for scale, is c. 5.7 cm (2.25 in) long. (Photo by the author)

Fig. 13.10 Splintering of a weathered radioulna of a common zebra (*Equus quagga boehmi*), weight 175–385 kg, caused by ungulate treadage near lake margin; fractures propagated along deep cracks created by columnar weathering into the medullary cavity. Death plus 6 years, Weathering Stage 4, East Lake Turkana, Kenya. Scale in 10 cm increments. (Photo by the author)

13.2.4 Trample Marks: Natural Mimics of the Stone Tool Edge

Some years after definition of SEM-derived criteria for stone tool cut marks to be described in Chap. 2, several researchers simultaneously noted marks on Miocene age bones that had the attributes of cut marks (Behrensmeyer et al. 1986, 1989; Fiorillo 1984, 1989). Since hominins had not yet appeared as a distinct lineage in the Miocene, "pseudo-cut marks" presented zooarchaeologists with a case of equifinality. To use Chap. 3's terminology, the effectors and actors creating cut marks and their natural mimics differ, one being a stone cutting edge in the hand of a hominin, the other being an angular grain of sand or gravel grating over a bone surface as an animal treads the bone against it. However, the actual causal process and context of production are similar: an irregularly shaped stone edge moving over a bone surface with enough force to produce a gouge. To ascertain what specific

Fig. 13.11 Trampling damage on a grand scale: crushed cranium of a topi (*Damaliscus lunatus*), average body weight 118 kg, in the bottom of a hippopotamus footprint in dried sediments near Lake Turkana's margin. Death plus 2 years, East Lake Turkana, Kenya (Photo by the author)

natural conditions produced "pseudo-cut marks," (Behrensmeyer et al. 1989) and Fiorillo (1989) and, later, Olsen and Shipman (1988) experimentally monitored hoofed animals' trampling effects on bones placed on various substrates. Experiments on sand and gravel substrates produced marks identical to those encountered in the fossil assemblages.

The problem was whether one could differentiate "pseudo-cut marks," or, more accurately, trampling marks (Domínguez-Rodrigo et al. 2009), from those inflicted by stone tools. Olsen and Shipman (1988) proposed general criteria for trample marks:

1. They may be finer, shallower, and wider than stone tool cut marks.
2. Their placement on bones is "random," in that they make less anatomical "sense" in terms of butchery than do true cut marks.
3. They may occur preferentially on convex surfaces.
4. They may be associated with development of polish on the bone.

However, Haynes (1991) noted that he found trampled, non-cut marked specimens from his elephant death study sites in Zimbabwe with each of the criteria proposed by Olsen and Shipman (1988) for true cut marks, and he called for more systematic research (see also Haynes and Krasinski 2010).

Domínguez-Rodrigo et al. (2009) published an experimentally based study aimed at distinguishing cut marks from trampling marks. They advocated developing, "the use of a low magnification approach (≤40×), which can enable the analysis of complete assemblages using either hand lenses or binocular lenses" (Domínguez-Rodrigo et al. 2009:2643), as SEM microscopy cannot. Their experimental procedures assessed the multiple and often mutually contradictory criteria for distinguishing cut marks from trampling marks in the literature, as well as whether their stated goal was possible.

The experiment monitored all variables previously noted in the literature, plus additional ones noted by members of the research team in other research contexts, totaling 16 in all (see Domínguez-Rodrigo et al. 2009: 2646–3647 for definitions of each). The study controlled for substrate (fine sand, medium grain sand, coarse sand, a mixture of all of these on a clay substrate, and gravel), duration of trampling, and elements trampled. The study also distinguished between cutmarks made by unretouched flakes and those made by retouched edges. Given the number of variables, the research employed multivariate analytic approaches to isolate the strongest correlations of effectors and effects perceptible at magnifications less than 40×.

The results indicated that marks made by trampling for longer than 2 min can by distinguished at magnifications less than 40× from cut marks using three of the 16 variables. This was true for cuts made by unretouched flakes and by retouched flakes. The authors cautioned that multiple criteria are essential because an overlap exists between trample marks and cut marks in each of these three individual traits.

For trample marks versus *unretouched* flake cut marks:

1. Seen from above, trample incisions in bone displayed more sinuous trajectories than do straighter-trajectory cut marks.
2. The cross-sectional shape of trample mark grooves are broader, with a _/ profile, while unretouched flake cut marks have a preponderance of V-shaped profiles.
3. Trample marks do not display the same shouldering and parallel grooves within the main mark that typical of cut marks (Chap. 14).

Domínguez-Rodrigo et al. repeat Behrensmeyer et al.’s (1986) caution that bones exposed to sustained trampling lose their microstriations through surface abrasion, so that the third trait may be unavailable in extensively trampled samples. To explore what the loss of striation features would mean for accuracy of distinctions between trample and cut marks, they ran a logistic regression analysis of the variables. This indicated that cross-sectional shape and trajectory alone could differentiate between trample marks and unretouched flake cut marks in 96.6% of their experimental sets.

Cut marks made by *retouched* edges often had _/ profiles similar to those of trample marks. However, Domínguez-Rodrigo et al. (2009: 2651) argued that multivariate analysis showed, trampling marks could be further differentiated from cut marks made with retouched flakes by the presence of shoulder effects and extensive flaking on the edge of the shoulder, as well as by the location of microstriations both at the base and on walls in the cut marks.” Domínguez-Rodrigo et al. (2009: 2645) defined flaking as “a continuous series of exfoliation of the shoulder edge, which can occur on part of the trajectory of the shoulder or on most of it.”

Domínguez-Rodrigo et al. (2009:2651) discuss distinguishing features for ambiguous pieces:

> Every single bone specimen subjected to trampling, irrespective of duration (10 s or 2 min), showed the typical microabrasion in the form of very shallow randomly distributed striae, which occupy various parts of the specimen. This microabrasion can only be properly identified with magnification (usually >10×).

They stipulate that these features were excluded from their experimental analysis because it is possible to find them both on trampled specimens and on ones that were cut marked and later trampled. This study offers a clearly defined template for replicative actualistic research on this topic.

Contextual analysis of archaeofaunal specimens' geological matrix and other inclusions – such as flaked stone debris – can facilitate evaluation of the likelihood of trampling-induced marks. Is the matrix sand or gravel, or is it too fine grained to have been the effector of the marks? If the matrix fine grained, are there some angular sedimentary particles in the deposit that could have made the marks? In my own work with East African pastoralist archaeofaunas, I see the presence of trample marks not as a distraction but as "part of the view" because high rates of these marks, in combination with abrasion on bone fracture and articular surfaces, suggest the action of hoofed animals within a settlement, hinting at space use and refuse disposal practices (Chap. 16 discusses abrasion).

13.2.5 Damage to Skeletal Elements During Life

Animals can suffer damage to their own skeletal elements in life, in the form of broken bones, tusks, and antlers, creating marks that may be confused with human modifications. Two types of modifications may be distinguished: traumatic injuries to skeletal elements through accidental fracture and subsequent bone pathology, and more common modifications of specific elements such as tusks and antlers during their use.

Haynes (1991:147–148) noted that, in the Hwange National Park, Zimbabwe, giraffe appeared especially liable to traumatic bone fracture. He illustrated fracture surfaces that became smooth through *in vivo* rubbing and abrasion. This kind of breakage would perfectly mimic fractures induced after death by other actors, and to date no research has been done to ascertain whether abrasion developed in this way differs from other forms of smoothing and polishing of bone break surfaces.

Modifications during life of a less traumatic nature occur on skeletal parts that directly confront the environment: teeth, horns, and antlers. Haynes (1991) noted that modern elephants routinely break tusk tips during scuffles over access to scarce water during drought years. These may mimic human polishing and flaking and very closely resemble objects alleged to be artifacts in several North American Paleoindian sites (Haynes 1991:Figs. 4.4 and 4.5).

S. L. Olsen (1989) studied unshed red deer antlers from 110 males and found the following types of damage to be common (Fig. 13.12):

1. Abrasion of the tines and parts of the beam, which could be confused with sedimentary abrasion.
2. Polishing of the tines and parts of the beam, which could be confused with abrasion caused by human use of antlers as tools.
3. Fractures at the tip of the beam, which might be mistaken for a broken point or awl tip made of antler.
4. Straight, shallow cuts on the beam ("marring"), which might be taken for cuts but lack the striations of cuts when seen under magnification.

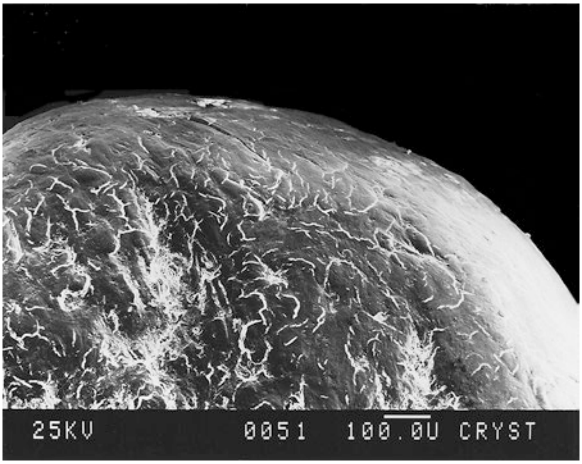

Fig. 13.12 SEM micrograph of natural polish and abrasion striations on deer antler tines, produced in life by a stag rubbing and thrashing his antlers against ground and vegetation. Scale bar 100 microns. See also Fig. 14.17 for antler percussor modification. (SEM micrograph by Sandra Olsen (1989:129 Fig. 2, used with permission of the author and Elsevier)

Olsen further investigated how to distinguish such modifications from similar ones that might develop postmortem if human use antlers as percussion tools. As illustrated in Fig. 14.17, Olsen's SEM study revealed some key differences to be discussed in Chap. 14.

13.3 Rodents as Bone Accumulators and Modifiers

Over their evolution, rodents have lost their lateral incisors and canines, retaining upper and lower first incisors that make distinctive marks on bone. In many rodent species, the incisors grow continuously, and rodents often gnaw on various objects, including bones. Some actually accumulate bones and other objects for gnawing. The need for minerals may motivate some such bone gnawing: captive Cape porcupines (*Hystrix africaeaustralis*) put on a low calcium diet directed twice as much gnawing to bones as did those on a higher-calcium regime. Zooarchaeologists should recognize the possible roles of rodent bone surface modification and accumulation of bones in forming an archaeofaunal sample.

Among the first investigations of rodents as bone accumulators was by researchers seeking to untangle the origins of South African archaeofaunas containing australopithecines. In his critique of Dart's ideas about hominin agency in these bone deposits, Hughes (1961) was among the first to note the bone-collecting habits of Cape porcupines which transport animal bones to their lairs. Brain (1981) reported an extensive collection of bones (and part of a bicycle) from one South African Cape porcupine den.

North American wood rats (*Neotoma* species), also known as pack rats, transport diverse objects, including bones, to their nests in caves, burrows, or abandoned human structures (Hoffman and Hays 1988). These accumulations are unlikely to be mistaken for human products when encountered in isolation, where they are useful in paleoenvironmental reconstructions (e.g. Lomolino et al. 1989). However, given wood rats' penchant for sheltered locales, they sometimes set up housekeeping in a cave, rock shelter, house, or pueblo previously used by humans. This presents zooarchaeologists with the problem of separating bones likely to have been introduced into the locale by wood rats from those attributable to human agency. Hockett (1989) sought criteria to help with this problem, analyzing modern wood rat nest contents from Gunnison County, Colorado. He found that simple measures of modification intensity were not helpful: 51% of all *Neotoma*-collected bones from nests displayed carnivore modification, and relatively few showed rodent gnawing marks.

13.3.1 Rodent Gnawing Marks

Rodent species appear to prefer gnawing dry compact bone over fresh, but Rabinovitch and Horwitz (1994) observed Asiatic porcupines (*Hystrix indica*) gnawing greasy bones, as have captive Cape porcupines. I have collected heavily rodent-gnawed specimens in California that retain a good deal of bone grease (Fig. 13.15), though no soft tissue. Rodents can gnaw an element lightly, leaving a few tooth marks on it, or they can gnaw so much that an element's osteological and taxonomical identifying features are removed. Brain (1981) and Shipman and Rose (1983) provide excellent illustrations at macroscopic and SEM magnifications of rodent modifications to bone. Morphological features can be summarized as follows:

1. Rodent tooth marks are relatively wide, being two more or less parallel troughs. The marks are slightly concave, reflecting the somewhat convex leading edges of rodent incisors (Figs. 13.13 and 13.14).

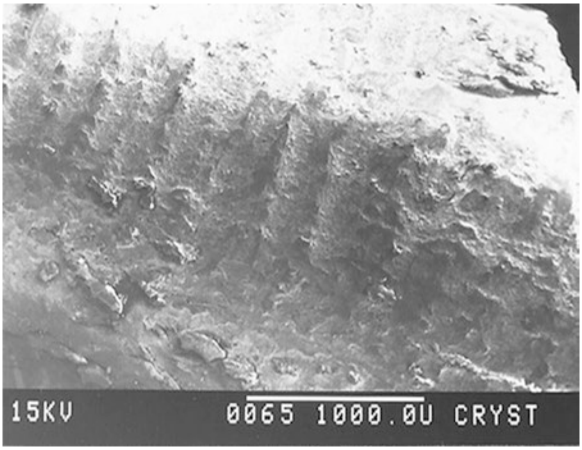

Fig. 13.13 SEM micrograph of a rodent-gnawed bone, showing ridges and troughs created by opposing first incisors scraping the bone surface. Note breadth, concavity, and regularity of spacing in relation to carnivore tooth scores (e.g. Fig. 12.1) (Unpublished SEM micrograph by Sandra Olsen, used with her permission)

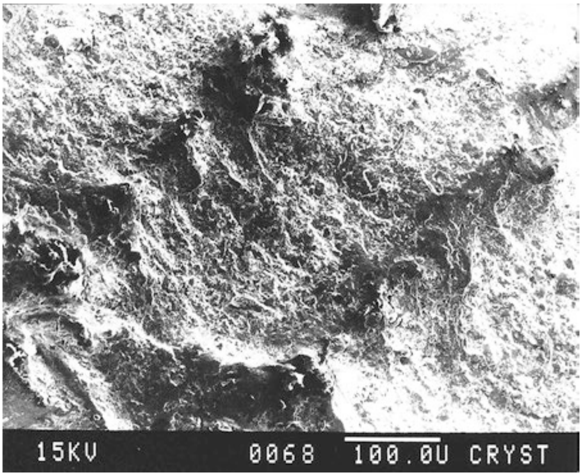

Fig. 13.14 SEM micrograph at higher magnification, showing details of the ridges and troughs created by opposing first incisors scraping the bone surface, as well as chatter marks transverse to the line of the trough caused by teeth "stuttering" over the bone surface. Scale bar 1000 microns. (Unpublished SEM micrograph by Sandra Olsen, used with her permission)

Fig. 13.15 A mule deer (*Odocoileus hemionus*) radioulna gnawed by rodents. Note the parallel-sided troughs formed in the bone by opposing rodent teeth and "sculpting" of the gnawed edge of the bone (Photo by Don Harris of specimen collected by the author)

2. Viewed closely, rodent tooth marks often display chatter marks, or ridges perpendicular to the main troughs, where the teeth skipped harmonically across the bone (Fig. 13.14).
3. Rodent tooth marks on one surface of an element or fragment have matching tooth marks on another side, made by the opposing set of incisors during gnawing (Fig. 13.16).
4. Rodent tooth marks may overlap one another due to repeated gnawing, sometimes making them difficult to distinguish in cross-section. They differ from V-shaped cut marks in their cross-section and lack of striations.

Maguire et al. (1980) have reported some furrowing by rodents in cancellous tissues in epiphyseal ends of long bones, as did Rabinovitch and Horwitz (1994), nearly always associated with distinctive rodent gnaw marks on compact diaphyseal bone. The inference is that rodents probably are the modifier creating the furrows. Burrowing rodents may gnaw bones after they are covered by sediments, although

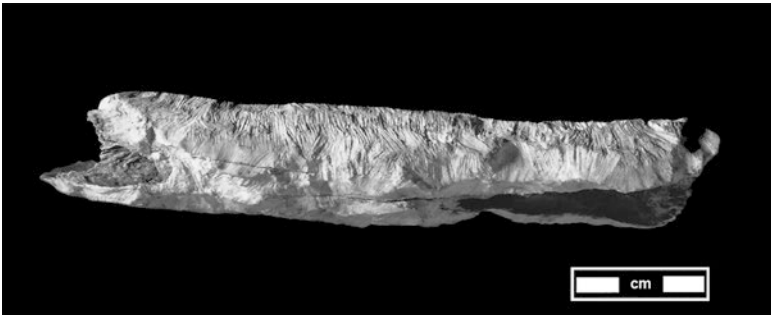

Fig. 13.16 A bovine (*Bos taurus*) metatarsal, showing very heavy gnawing by rodents, with the bone's overall shape altered by the gnawing (Photo by Don Harris of specimen collected by the author.)

they do not appear to gnaw diagenetically altered bones. Rates of gnawing in wild *Hystrix indica* porcupine accumulations evaluated by Rabinovitch and Horwitz were relatively low, under 10% of the entire accumulated assemblage. As foreshadowed in this discussion, the next chapter turns to human tool-mediated modifications to bone.

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Chapter 14

Primary Human Effects: Cutting Edge and Percussion Effects on Bone

Humans seldom eat vertebrates whole. Even animals weighing no more than a kilogram are broken into smaller segments before being chewed and swallowed. This pedestrian observation has broad implications for zooarchaeology. Bones of animals that humans consume often bear traces of how they were dismembered and their edible tissues were extracted. This chapter reviews what is known about the nature and causes of various primary human modifications to bone. It introduces distinctive bone surface modifications made by tools: cuts, scrapes, chops, and a range of percussion marks. I call these "primary human effects," in recognition of the temporal priority of these activities in relation to subsequent culinary processing reviewed in Chap. 15. "Primary" also acknowledges the greater antiquity in human history of tool-mediated carcass subdivision and percussion-aided nutrient extraction, which preceded cooking with fire by at least a million years. Chapter 15 will review heat-mediated processing and other tactics for enhancing the nutrient value or extending the use–life of animal foods. As with the signatures of nonhuman actors discussed in prior chapters, these chapters focus on distinctive human tool signatures and the contexts in which they are produced.

Butchery refers to human subdivision of vertebrate bodies into smaller units with tools. Research on butchery thus presents archaeologists with rich inferential possibilities, but these are fraught with interpretive complexities, and using clear terminology helps maintain important distinctions. Lyman (1987a:252) noted that butchery is not a single act but a sequence of activities. These actions are guided by a variety of considerations, including the anatomy of the animal, the implements at hand for processing it, the weather and time of day, the butchery site's distance from the final destination of the animal products, the intended uses of the animal's tissues, and so forth.

Some distinctions are useful to thinking about the sequence of operations involved in butchery. I refer to the first step in processing a carcass, usually shortly after an animal's death, as *primary butchery*, a generic term that applies equally well to hunters, pastoralists, farmers, or specialized meat processors. This is equivalent to Lyman's (1987a) "kill-butchery," also called "field butchery" by some

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working with hunters. Primary butchery may involve eviscerating, skinning, and dismembering the carcass and defleshing some of its parts.

Secondary butchery may take place at a different locale than primary butchery. For example, body segments transported to a caching locale may be further subdivided and trimmed at that locality to facilitate storage. Among hunters, carcass segments that served well for transport to a residential base may be subdivided according to the needs and desires of households sharing in the kill when those parts arrive at the camp. Secondary butchery can involve both dismemberment and defleshing.

Culinary processing (Chap. 15) is associated with cooking and eating animal bodies. It takes place not only at residential locales but also afield, as individuals or task groups sustain themselves while traveling to obtain resources away from their home bases. Hunters may consume snacks or meals during primary butchery, focusing on tissues that are liable to swift spoilage such as the brain and internal organs. People guarding cultivated fields a distance from a village may set up camp there, acquiring vertebrates during their time away from home and discarding bones in their field camps. Culinary processing involves further dismemberment and defleshing prior to cooking, reduction of bones by chopping and breaking to fit cooking containers and to liberate fat into stews, reduction of marrow-bearing bones by chopping and fracture, and exposure of bones to heat by variants on boiling, roasting, or baking.

Preservational processing, preparing meat, fat, or marrow to extend their use-life, is discussed in Chap. 15 and only briefly treated here with reference to evidence added during the chain of sequential butchery operations. Preservational processing includes meat stripping, drying, smoking with bone in or not, salting, pickling, mass marrow extraction, and bone grease extraction. Some operations leave distinctive signatures, while others do not.

Our knowledge of human modifications to bone has expanded through contemporary observations of actors in ethnoarchaeological and experimental settings. As with nonhuman bone surface modifications, SEM microscopy has clarified distinctive signatures of specific effectors. This chapter reviews basic morphological criteria of cutting and percussion modifications to bone. It leaves discussions of how to infer broader behavioral, social, and ecological contexts in which these modifications were produced for Part V.

14.1 Marks Made by Cutting Edge

Cutting marks can be inflicted on bone during dismemberment, defleshing, skinning, and removal of periosteum. The main intent of this chapter is to describe distinctive features of bone surfaces modifications at the effector/actor level of impacts. Discussion of the controversies over the functional meanings of cut mark patterning will be deferred until Chap. 19, which discusses inferring butchery from aggregate data.

Most actualistic research on distinctive criteria of cut marks has focused on stone tool marks. When referring to "stone tool cut marks," most researchers mean slicing marks made by cutting tools fashioned by percussion or pressure flaking, rather than by edges formed by grinding and polishing. Paleoanthropological researchers seeking to discern hominin behavior from sparse, Plio-Pleistocene evidence have done much of this topic's basic actualistic research. Their aim was to distinguish traces of hominin intervention from those of carnivores in palaeolithic African and Eurasian sites. More recently, zooarchaeologists studying societies in transition from stone to metal implements have explored the potential of cut marks on bone to elucidate how ubiquitous metal tools were in daily life by conducting parallel experiments.

Recognition of stone tool cut marks in 1981, and Binford's (1981) imputation of functional meaning to their placement on different skeletal elements (Chap. 15), led to a boom in studies discussing the behavioral contexts in which they had been made, especially among paleoanthropological researchers. Lyman (1995, 2005), wrote two thoughtful articles exploring the assertion that functional inferences could be made from cut mark frequencies. In these, he systematically investigated the placements and counts of cut marks and percussion marks on ruminant bones from multiple archaeofaunal samples from a total of eight archaeological sites in the Pacific Northwest of the U.S. His first study (Lyman 1995), compared archaeofaunas from three coastal Oregon sites with three from eastern Oregon, focusing on deer (genus *Odocoileus*) and wapiti *(Cervus elaphus*, known as "elk" in North America) and remains of like-sized ruminants. The second compared two more or less contemporaneous sites, Meier and Cathlapotle, within 10 km of each other on the lower Columbia River. Though Lyman found some statistically significant differences between the rates of occurrence of processing marks between coastal and inland sites that might arise from ecologically conditioned differences in the importance of ruminant-derived nutrients in the respective regions (Lyman 1995), however, he also found significant differences in cut mark frequencies in sites within the same geographic areas (Lyman 1995, 2005).

At the heart of the problem is the fact that, unlike chopping, sawing, or percussion marks, cut marks cannot be assumed to result from consistent and deliberate intention to impact the bone surface. Lyman concluded that cut mark analyses must be used along with other contextual evidence in *multivariate analysis* of butchery behavior, and not as a freestanding measure of intensity or intention of processing. Lyman's research thus cautions zooarchaeologists to avoid ampliative inferences about behavior from "cut mark intensity" and placement. The problem is not that cut marks do not ever convey useful information for reconstructing soft tissue removal. Rather, it's that their rates of occurrence and placements on skeletal elements are so highly variable, and generated in such presently unknowable contexts (was the bone and meat raw or cooked?) that using them to make higher-order inferences is often unwise. Those that do occur, taken together with other evidence for handling, may hint at, rather than establish, certain modes of carcass handling. Therefore, understanding their physical hallmarks is worthwhile.

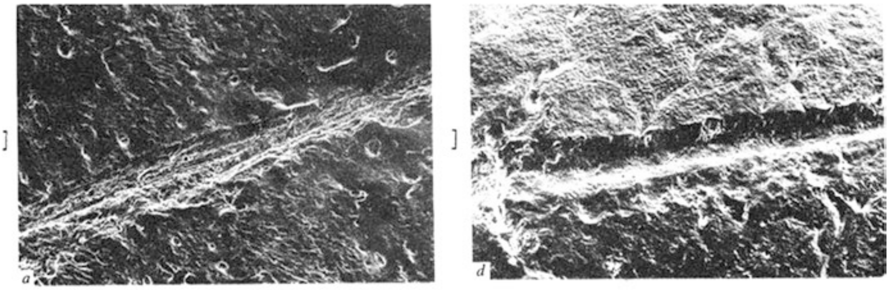

Fig. 14.1 An experimental stone tool slicing mark (**a**) and a hyena tooth score (**d**). Note striations in the cut mark, undulating chatter marks at base of the carnivore score mark. Brackets to the left of each micrograph represent 100 microns. (From Potts and Shipman (1981:578, Fig. 1), used with permission of the authors and Springer Publishing)

14.1.1 Flaked Stone Tool Cut Marks

The morphology of stone tool cut marks was described by Potts and Shipman (1981), Bunn (1981), Shipman and Rose (1983); see also reviews by Noe-Nygaard (1989) and Fisher (1995) on bone surface modifications. Shipman first applied SEM microscopy to defining morphological traits of stone tool marks (Fig. 14.1). Characteristics of stone tool cut marks noted by Shipman & Rose (1983) include:

1. Marks have most commonly V-shaped or oblique V-shaped cross-sections, but marks may occasionally be U-shaped (see below).
2. Stone tool marks show little crushing of bone into the groove of the cut mark.
3. Multiple striations lie in the groove, running generally in parallel to it.
4. Striations may deviate from the main groove on to the bone surface, as "shoulder effects."
5. The beginning or end of the main groove may show striations diverging from the main cut (Fig. 14.2).
6. Relative to most carnivore tooth marks, cut marks are more elongated.

On the basis of further experimentation, one can add to these characteristics a relatively straight trajectory to the incision (Domínguez-Rodrigo et al. 2009, Chapter 13).

Stone tool edge morphology determines the cross-sectional shape and specific details of the cut marks they make. Walker and Long (1977)'s classic experimental study produced cut marks on fresh bone using metal implements, stone flakes with the unmodified edges, and stone tools with edges shaped (retouched) by further flaking, study the cuts with low-magnification light microscopy. They noted:

1. Unretouched flakes usually leave V-shaped marks.
2. Retouched tools leave more U-shaped marks, or, as Domínguez-Rodrigo et al. later (2009) put it, _/ shaped marks, which are wide but have relatively straight, oblique sides.

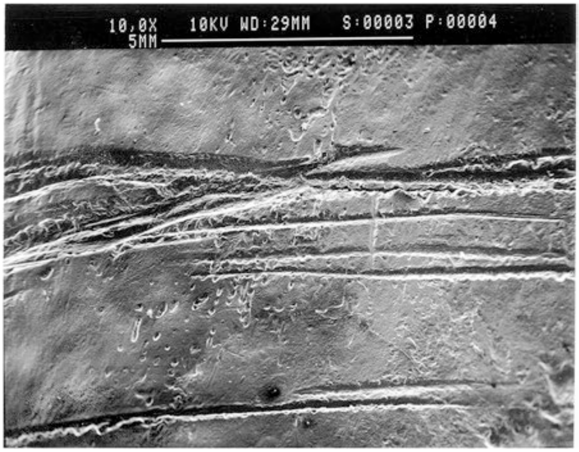

Fig. 14.2 Cut marks on bison thoracic vertebra, Koepke Site, I-74. Note sub-parallel striations within the main groove of the largest cut mark, "barb," and "shoulder effect" to left of and above main groove (Photo from Fisher (1995:13, Fig. 2a), used with permission of author and Elsevier)

Cut marks from retouched implements may display continuous exfoliation along part or all of the shoulder edge (Domínguez-Rodrigo et al. 2009, see Chap. 13).

The distinctive striations of stone tool cut marks are produced by irregularities in the stone tool edge that leave multiple fine lines in and at the edge of the main groove as the tool incises a bone surface. Even an unretouched flake edge has irregularities: flakes struck from a stone core are not flat but rather curved in profile, reflecting the wave of force that caused the flake release. A slicing action draws this curving edge over a section of bone, which contributes to multiple "paths" of striations, which may be may be augmented by edge damage or eminences in more granular raw materials. Retouched edges are even more complex: the ridges delimiting multiple small flake scars that shape a tool edge come into contact with the bone during a slicing action.

Haynes (1991:163) and Lyman (1994:297) stressed that Shipman and Rose's criteria derived from experimental study of direct cutting into bone, rather than from marks made incidental to cutting soft tissue during butchery. They note that not all distinguishing features noted in such experiments may be present in actual butchery cut marks, because the periosteum and other soft tissues can shield bone surfaces from the edge's impact. Shipman and Rose (1983: Figs. 5a, b) illustrate cuts into periosteum and the same marks on underlying bone after removal of the periosteum.

While some initially argued that SEM microscopy was the only accurate means of establishing that a mark was indeed inflicted by a stone implement, most zooarchaeologists have concluded that diagnostic traits of stone cut marks are recognizable under relatively low magnification light microscopy on well-preserved bone surfaces (e.g. White 1992; Domínguez-Rodrigo et al. 2009). I have been able to discern striations and barbs with magnifications ranging from a 10× hand lens to 50× light microscope. Some marks are indeed ambiguous when viewed at such low magnifications, and if a major research question can only be answered by determining the effector and actor, SEM examination can resolve such ambiguities (Blumenschine et al. 1996; Lyman 1987b).

14.1.2 Metal Cut Marks

Metal tool marks have been investigated using both SEM and more recently developed imaging techniques. Discerning whether metal tools were used to process an archaeofauna is relevant for several reasons. Shifts from stone- to metal-based butchery technology can entail reorganization of hunting, carcass processing, selective transport, and culinary strategies. This transition may indirectly reflect major changes in social relations: not everyone in a community may possess esoteric metallurgical knowledge and technical skills, thereby differentiating those with such knowledge and skills from others. Some groups obtain metal tools by exchange with metallurgical specialists in other societies, which may intensify raw material and commodity production in the recipient society, as well as inter-societal relations. Finally, access to high-value metal tools can vary within a community, according to the wealth and social networks of different households. Intra-community variation in metal-mediated versus stone-mediated carcass processing may shed light on social asymmetries at the level of households or gender (Gifford-Gonzalez 1989b).

The earlier literature (Binford 1981; Gifford-Gonzalez 1989a; Lupo 1994; Walker and Long 1977) reached a consensus about metal cut marks:

1. They lack fine striations within the groove.
2. They are often more steeply V-shaped in cross-section than are stone tool marks.
3. They often have an obliquely angled cross-section.

Further research expanded on typical features of metal tool marks on bone. S. L. Olsen (1988) used SEM microscopy to examine marks made during bone tool manufacture, including those created by metal implements, revealing distinctive scrape marks compared to those made by stone implements. Greenfield (1999) experimentally explored effects of metal cutting edges of varying types, scalpels to large knife blades, as well as smooth versus serrated knife edges, reporting SEM microscopy findings for simple metal blade effects:

1. Metal blades generally produce either a narrow V-shaped groove with a distinct apex at the bottom of the mark (Fig. 14.3). In the case of duller edges, metal blades can produce a more square, [_]-shaped groove with a flat bottom.
2. Metal blades produce more uniform cuts.
3. Metal blades tend to build up a ridge of bone to one side of the incision that Olsen (1988) called “crushing-up” (Fig. 14.4), a more ubiquitous trait of sharp, straight metal cutting edges than of stone tool cut marks. Greenfield notes that stone tool cuts may appear dirty under magnification due to a trail of microdebris in the groove (Greenfield 1999:804).

Although metal cut marks lack the striations typical of stone tool cut marks, metal knives with dull or damaged edges may leave one or more parallel grooves within the main cut, which might be mistaken for stone tool marks by those unfamiliar with lithic cut marks on bone. The grooves within a metal cut differ from striations by normally being consistent in their placement throughout the entire cut

Fig. 14.3 Metal cut marks on the anterior face of a caprine lunate (carpal bone) at 20× magnification, showing cut marks in a z-pattern on the bone. Specimen from the seventeenth century Spanish colonial era site of Paa-ko/San Pedro (LA-162), Bernalillo County, New Mexico (Photo by Jun Sunseri, used with his permission)

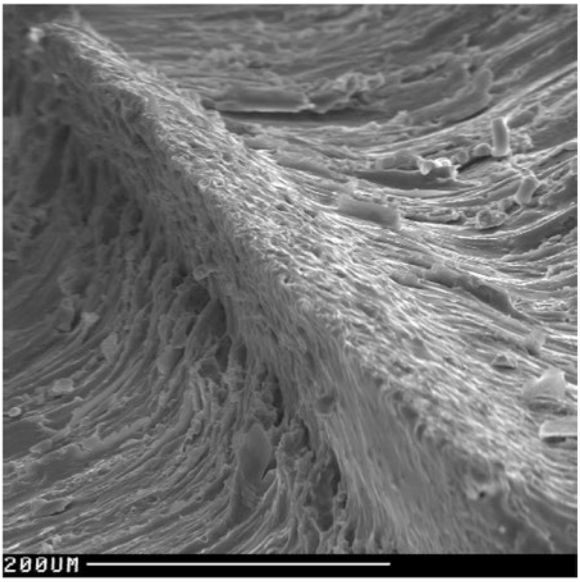

Fig. 14.4 SEM micrograph of modern metal knife cut mark at 200× magnification, showing the crushing-up of a section of bone cut by the blade (Greenfield 1999:801, Fig. 3, used with permission of author and Elsevier)

and not "shouldering out" as do stone tool striations. Figure 14.5 illustrates a metal tool mark on conjoined caprine cranial fragments from a seventeenth century colonial site in New Mexico. Forensic anthropologist Alison Galloway (personal communication, 2002) notes that such marks are relatively common in criminal cases, as perpetrators may resort to relatively dull kitchen knives or craft-bench tools at hand when hurriedly breaking down a victim's body.

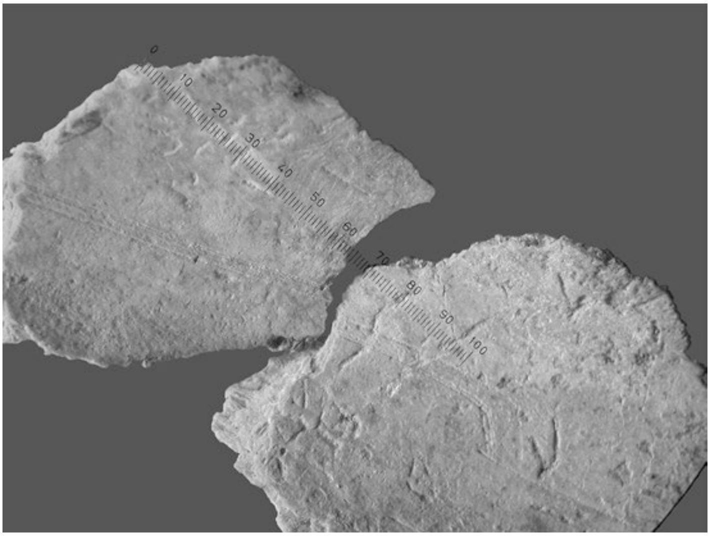

Fig. 14.5 Metal cut mark on caprine cranial fragments at 10× magnification, showing a broad mark with a consistent, unshouldered parallel groove within the main scar. Such marks are made by dulled or damaged metal tool edges. Scale calibration in mm. Specimen from the seventeenth century Spanish colonial era site of Paa-ko/San Pedro (LA-162), Bernalillo County, New Mexico (Photo by Jun Sunseri, used with his permission)

14.1.3 Scrape Marks

The same stone and metal edges as can incise bone surfaces can produce scraping marks when their edges are dragged at an angle across a bone surface. Scraping accomplishes a number of goals during carcass processing, including during disarticulation, when clearing off soft tissues before cutting a tendon or ligament at a joint, or during marrow extraction, when scraping periosteum off a long bone surface before striking it with a percussor to break the bone (Binford 1981). Shipman and Rose (1983) characterized scrapes made by stone flakes:

1. They display broad, shallow grooves over 1 cm^2 or more.
2. The have parallel striations in sets, possibly with multiple, differently oriented sets intersecting in the scraping scar (see also Lyman 1987a).

The nature of the tool and its orientation to the bone surface condition the configuration of marks produced. Figures 14.6 and 14.7 show differences in modifications produced by different stone tool forms and edge orientations.

Christidou (2008), who has investigated Late Neolithic and Bronze Age fauna in the Balkans, reported on experiments with bronze replicas of cutting and engraving tools found in regional sites. Experiments included scraping, whittling, grooving, and percussion of sheep/goat metapodial bones, with scraping tools applied at different angles to the bone surface. Resulting marks were examined under a 5-50×

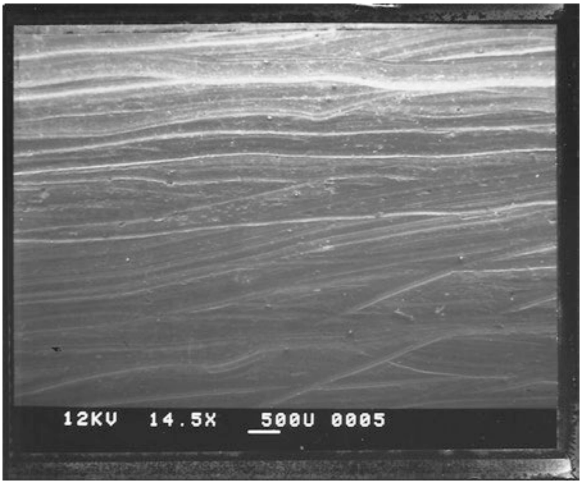

Fig. 14.6 SEM micrograph of fresh bone scraped with an unmodified flint blade. Scrape shows longitudinal striations typical of cuts with stone tools, but with the flake held more or less perpendicular to the surface of the bone. Striations thus cover the entire scraped surface, rather than being confined to a cut. White bar in footer is 500 microns. (Unpublished SEM micrograph by Sandra Olsen, used with her permission)

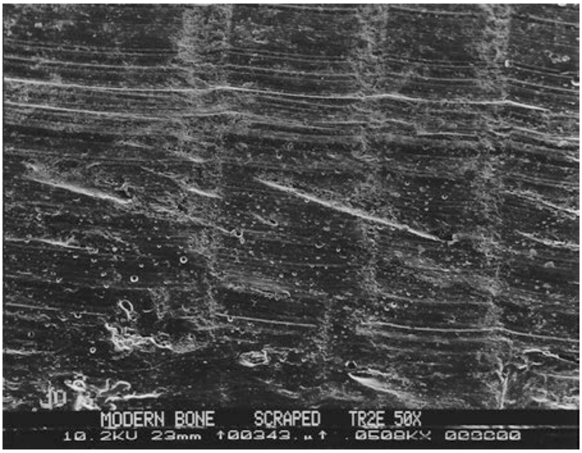

Fig. 14.7 SEM micrograph showing longitudinal striations made on fresh bones by scraping with a flint burin, or engraver. Horizontal striae are micro-cuts from the edge of the tool; vertical lines are chatter marks created as the tool skipped repeatedly across the bone surface. Blurred bar in footer bar: 1000 microns. (Unpublished SEM micrograph by Sandra Olsen, used with her permission)

stereoscopic light microscope, and with a metallographic microscope using Differential Interference Contrast (DIC) polarized light microscopy at 200× magnification, which produces a somewhat three-dimensional view that enhanced features of tool traces. Christidou (2008:750) summarizes features of the experimentally produced modifications: metal tool scraping marks exhibit a generally more uniform pattern of scratches than marks made by stone tools and may include chatter marks (Fig. 14.8). Repeated scraping with metal tools produced polish by spreading and smoothing cortical bone fragments along the bone surface.

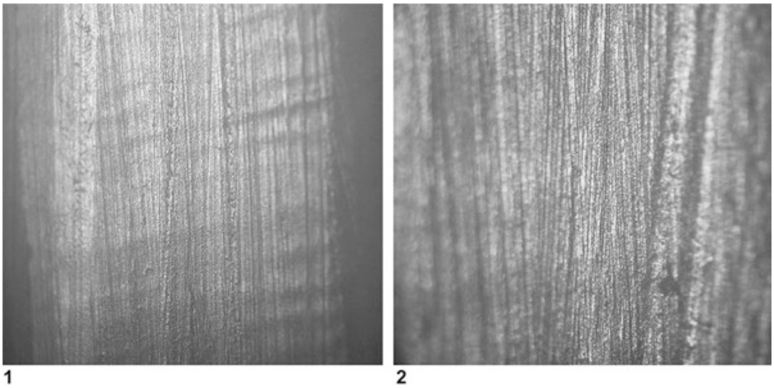

Fig. 14.8 Caprine metapodial surfaces scraped by bronze knife blade, micrograph taken with stereoscopic microscope. **1** 12.5×; **2** 40× magnification (From: Christidou (2008:736, Fig. 2), used with permission of Elsevier)

14.1.4 Chop Marks

Chop or hack marks are percussion marks inflicted by sharp-edged tools and have been recognized as a distinct form of butchery modification for many years (e.g. Guilday et al. 1962). Chops or hacks can be made with either stone or metal tools. Chop marks may be inflicted during primary butchery, during disarticulation of joints, or removal of edible tissues from larger animals. Frison (1970) argued that prehistoric peoples of the Great Plains used chopping to swiftly remove quantities of meat from mass bison kills. Chopping can also occur in secondary or culinary carcass processing. Depending upon the nature of the cutting edge and mass of the tool, chopping can break down skeletal units for social distribution (Bartram 1993; Yellen 1977), to fit them into a cooking pot (Bartram 1993; Yellen 1977; Marshall 1986), or to open marrowbones (Yellen 1977, 1991). Binford (1981) recorded chopping with metal hatchets as a regularly applied tactic for breaking up frozen segments of butchered caribou among the Nunamiut.

As with other forms of percussion, chopping may not leave tool marks on all fragments it produces. Chop marks are inflicted to the depth that a chopping tool penetrates the element struck, and the force front perpetuated by its blow creates a typical break surface through the balance of the element. Bone that is successfully chopped through generally displays:

1. A planar, flat surface on the chop mark itself. Walker and Long (1977) report a higher depth-to-width ratio of chop marks as opposed to cut marks, and Shipman and Rose (1983) report that chop marks are wider than cut marks at top.
2. If compact and cancellous bone tissues are transected, both are flattened in the same plane. This contrasts with the response of these respective tissues to blunt percussion. If cancellous bone is chopped, some trabecular tissue may be crushed into adjacent pore spaces.

3. Fractures may arise and run on from the point of deepest penetration of the tool mark, showing a discernible shift in the surface contour of the break.

I have found that *unsuccessful* chop marks often reveal more of the shape of the chopping tool than do successful chops, which dissociate the cross-sectional evidence of the tool.

A single tool used for chopping can sometimes be employed in finer-grained cutting as well, thus leaving two disparate signatures. A good example of this is the Asian metal cleaver. Most non-Asians view this implement as a chopping tool, but it is actually used for filleting, fine slicing, and dicing. At the experimental zooarchaeology workshop that I ran outside Beijing in 1992, Chinese colleagues shunned my knife in favor of the more familiar – and very sharp – cleaver for skinning a goat. They quickly accomplished the skinning operation with a minimal number of cleaver cuts to the skin, combined with skilled manual separation of connective tissue holding integument to the rest of the carcass.

14.1.5 Saw Marks

In sawing, the force applied by the tool moves back and forth at an acute to right angle to the orientation to the bone surface, normally with downward pressure and in constant contact with the bone surface. These marks can be made with stone or metal tools. Carcass processing using metal saws is the hallmark of urbanized European butchery for centuries: medieval European paintings and stained glass windows attest to butchers' use of metal saws to break up carcasses of pigs and cattle. Sawing sections of one or more skeletal elements to produces the finished, bone-in cuts of meat with which Westerners are familiar (Gust 1983, also see Fig. 14.9).

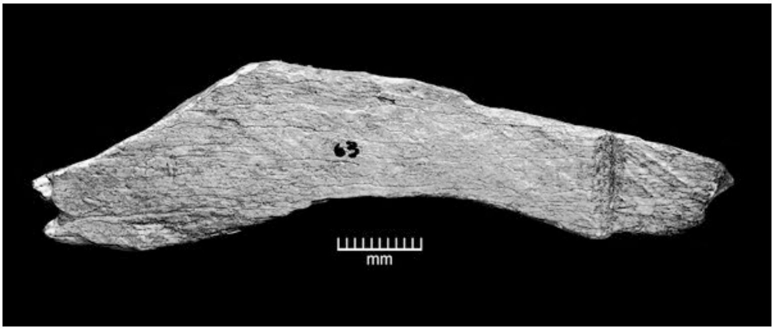

Fig. 14.9 Fragment of a flat bone of a very large mammal, showing a broad stone tool saw mark, striations from sedimentary abrasion, Behrensmeyer Weathering Stage 3. Bone associated with an Upper Pleistocene Aterian lithic industry locality near Adrar Bous, Niger. (Photo by Don Harris, of a specimen collected 1970 by J. D. Clark, in an assemblage analyzed by the author)

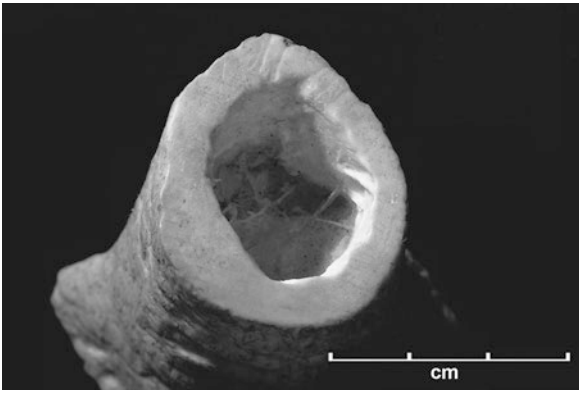

Fig. 14.10 Close-up photograph of a modern long bone cut with a metal band saw, showing the plane, flat surface, and fine parallel striations across the surface made by the saw teeth. This specimen's surface is overprinted by some angled carnivore tooth scores on the upper right quadrant on the circumference, as well as rounding and polishing of bones due to carnivore gnawing and licking. Scale shows 1 cm intervals. (Photo by Don Harris, of a specimen collected by the author)

Stone tools and metal ones can leave sawing marks with the following characteristics:

1. Stone tools used in a sawing motion leave a wide scar, usually in a parallel series, with striations (Walker and Long 1977).
2. Stone tool sawing marks may have an undulating aspect when viewed from above.
3. Serrated metal sawing tools produce regular, fine parallel striae across the flat sawed surface. Gust (1983) illustrates historic saw marks on butchered bone compared with those produced by a modern band saw. Historic marks are generally coarser than modern saw marks.
4. Bones sawed with metal tools display "hinges" on sawed and then broken surfaces, chipping, oblique or straight angles, and incomplete stroke marks.
5. Under magnification, the surface of sawed cancellous tissue displays small bone fragments crushed into the trabeculae transected by the saw (Figs. 14.10 and 14.11).

14.2 Products of Percussion: Hammerstone Notches, Pits, Anvil Damage

Percussion by humans is dynamic loading via hard percussors, aimed at breaking open skeletal elements to extract within-bone contents. Hominins have been hitting diaphyseal segments of marrow-bearing long bones with hammerstones for well over two million years (Blumenschine and Selvaggio 1988), a practice that continues to the present day. Percussion results in an array of bone surface modifications with specific morphological features (cf. Blumenschine and Selvaggio 1988, 1991;

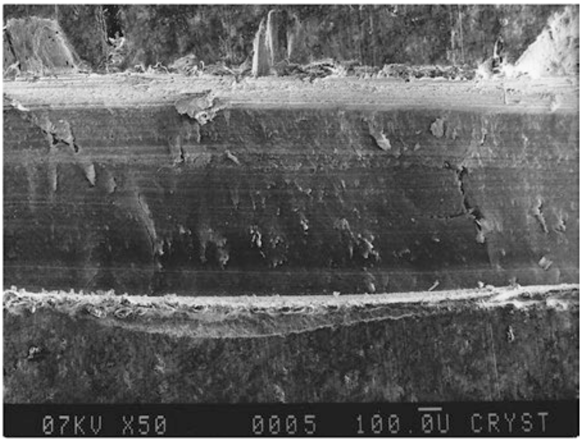

Fig. 14.11 SEM micrograph of a toothed metal saw mark on fresh bone, with broad, consistently straight-sided marks of individual saw teeth along the top edge of initial contact, with crushing-up of bone tissue at both edges and crushing of bone tissue into the mark. Note that parallel striations in the bottom of the saw mark are nearly perfectly straight for extended distances. Scale bar on footer = 100 microns (Micrograph by Sandra Olsen, used with her permission)

Fisher 1995; Lyman 1994). Controlled experiments (Galán et al. 2009; Blasco et al. 2014; Pickering and Egeland 2006) have augmented descriptions of their diversity in form and added greater complexity to identifying the mechanical causes of specific marks.

Ethnoarchaeological and experimental observations show that, in the absence of ground or metal stone chopping tools, one of several tactics may be applied to break long bones. One is striking an element in the hand with a percussor, as Binford (1978, 1981) reports is typical of Nunamiut processing fresh caribou elements. A widely used approach involves resting an element on an anvil of stone or bone and striking its upper side with a percussor. Stone anvils enhance the fracturing potential of a hammerstone blow by reflecting the force transmitted through the bone to the anvil back into it (Johnson 1978, 1983; Mengoni Goñalons 1980). Chapter 11 described that some force introduced into a long bone cylinder by percussion winds around and along the element, as other force runs transversely across the bone. If this meets an anvil, it rebounds into the element, amplifying a single blow's stress on the cylinder. Another technique is striking a skeletal element against a stationary rock anvil (Blasco et al. 2014). Readers may be more familiar with outcomes of striking a bone with a stone or other hard object, but less so with striking a stone or other hard anvil with a bone. Both are approaches will be discussed here.

Blasco et al. (2014) undertook experimental trials to compare fracture and bone surface modification of hammerstone percussion, both with and without an anvil, to those produced by anvil clubbing percussion (Oliver 1993), or, as Blasco et al. call it, batting percussion (readers from cricket- or baseball-playing countries are permitted a moment to adjust their referential frames). Six individuals with no prior experience with breaking long bones each fractured four fresh humeri, four

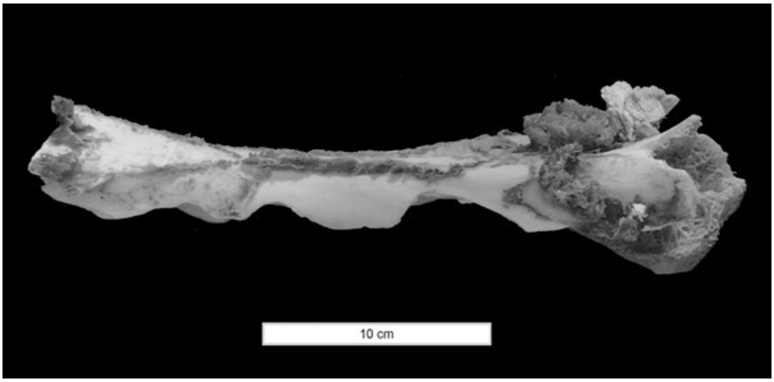

Fig. 14.12 Femur of topi (*Damaliscus lunatus*) from a modern foraging campsite near Koobi Fora, East Lake Turkana, Kenya, showing three hammerstone impact notches (Photo Don Harris of a specimen collected by author)

radioulnae, four femora, and four tibiae of mature domestic cattle using each of the approaches. They were given little instruction in procedures, and their intuitive choices and learning curves were documented. In the batting/clubbing experiment, the experimenters held the element in both hands and struck it against a limestone anvil with rounded edges until the bone broke. If the element did not break on the first try, all actors chose to keep striking the same part of the long bone on the anvil until it did. On average, actors assigned bones in the batting/clubbing experiment broke them in one-third the time spent breaking bones using hammerstones; average time to fracture was less than 30 s.

Bone surface modifications produced by all forms of percussion result from the interaction of an element and its surface with a hammerstone, an anvil, and/or a stone against which it is struck. These interactions produce larger and smaller marks that testify to the use of percussive force and are outlined below.

14.2.1 Hammerstone Impact Notches

Impact notches, or, more neutrally, "loading points," are the most distinctive percussion marks. Such marks usually are semilunar concavities along the broken wall of a diaphysis. In direct or anvil percussion, depending upon the relation of diaphysis size and strength to strength of the hammerstone wielder, and also the processor's expertise, only one blow may be sufficient to crack a long bone open. Several blows may be required to weaken the cylinder, and each blow will be reflected in a distinctive notch (Fig. 14.12). These are actually flake scars (see *Percussion Flakes* below). Capaldo and Blumenschine (1994) provide a comprehensive review of zooarchaeological discussions of notches up to the point of their article. Pickering and Egeland (2006), Galán et al. (2009) and Blasco et al. (2014) augment this review and add more experimental results.

Earlier experiments concluded that notches were formed only on the side of a long bone directly struck by the hammerstone, with the associated flake or flakes driven off on the endosteal side of the bone. Later experiments by Galán et al. (2009) have raised the possibility that, occasionally, impacts can create notches on both hammerstone- and anvil-sides of a long bone, or opposing notches.

As might be expected, the clubbing/batting approach of the Blasco et al. (2014) study produced some bone surface modifications similar to hammerstone percussion and some that differed. Percentages of impact notches were actually similar in the hammerstone and batting assemblages, but the proportions of multiple notches differed. The combined hammerstone sample had 70% single notches and 28% multiple, overlapping notches, whereas the reverse was the case with the batting assemblage, which displayed 70% overlapping notches and 30% single notches (Blasco et al. 2014: 1077). This is due to the repeated striking of the same part of the element against the anvil described above. The hammerstone sample had 2% opposing notches, per Galán et al. (2009), whereas the batting sample had none. Divergences were also seen in the relation of notches to the long axis of the element: batting percussion, "concentrates impacts on transverse planes," whereas notches from hammerstone percussion "occur on all type of planes, except on transversal ones" (Blasco et al. 2014: 1099).

14.2.2 Percussion Flakes

Other traits are associated with impact notches. Most apparent are those small percussion flakes detached from the medullary side of the diaphyseal wall at the impact point, which create the notches described above (Fig. 14.12). Fisher (1995:21) notes that percussion flakes, "display the same basic technical attributes of percussion as occur on flakes of knapped fine-grained stone" (Fig. 14.13):

1. They display a platform at the impact point and a bulb of percussion below the platform.
2. They sometimes show "ripple" marks and/or hackle marks originating at or near the platform or bulb.
3. Such flakes usually are side-struck (wider-than-long) in morphology and may display stepping at their distal ends.

In Blasco et al.'s hammerstone sample, impact flakes accounted for 13% of all diaphyseal fragments, whereas they accounted for only 0.9% of all fragments generated by batting bones against an anvil (Blasco et al. 2014: 1089–1093).

Another type of damage at the impact point is crushing along the outer wall of the diaphysis, which may be discernable as isolated pits (see below) or may be a continuous field of such damage.

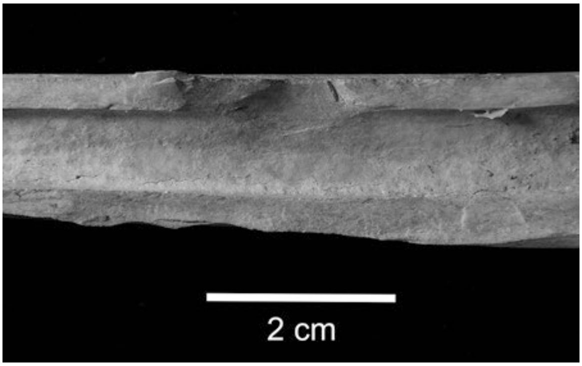

Fig. 14.13 Percussion flake scar on endosteal side of a pronghorn (*Antilocapra americana*) metatarsal from the Lost Terrace site, Montana. Note the typical side-struck form, with breadth greater than depth in relation to the direction of force. (Photo by John L. Fisher, used with permission)

14.2.3 Anvil Counterblow Damage

The in-bound force from a percussor blow often interacts with the force rebounding from an anvil to cause shatter on the outer surface of the anvil-side diaphyseal wall. This "counterblow" damage to a long bone differs from that of a hammerstone impact, often manifesting as angular shatter on the outer side of the diaphysis wall rather than as conchoidal flakes detached on the inner, medullary side of the wall.

14.2.4 Percussion Scratches and Pits

Hammerstones and anvils may be stones with irregular surfaces or smooth cobbles. When the initial blow drives a bone against an anvil, several marks are possible. Prominences on the stone dig into the bone surface, often dragging across it with lateral movement of bone with the swinging blow by the hammerstone. Turner (1983) termed such marks "anvil scratches" on the assumption that these appeared exclusively on the anvil side of diaphyses. Blumenschine and Selvaggio (1988, 1991) defined percussion pits and depressions with "microstriations" associated with hammerstone notches (Figs. 14.14 and 14.15). Pickering and Egeland (2006) follow White's (1992) separation of these percussion marks into two types, pits and striae fields, while acknowledging that these categories may overlap. They determined that the majority (68%) of percussion pits on experimentally fractured deer long bones were from the anvil side of experimental bones, as were striae fields (72%), while around one-third were associated with hammerstone impacts on the upper surface of the long bone.

Percussion pits with striations leading out of the pits were originally seen as a hallmark of this modification (Fig. 14.15). However, Galán et al. (2009) explored the consequences of using smooth- versus rough-textured hammerstone-anvil combinations. They found the same percussion marks documented by other researchers but also a third type of percussion mark, a pit without microstriations (Fig. 14.16).

Fig. 14.14 Experimentally produced stone anvil percussion pits (right) and striae field (center) on a bovid long bone, at c. 16× magnification (Photo from Blumenschine et al. (1996:498, Fig. 2d), used with permission of Elsevier)

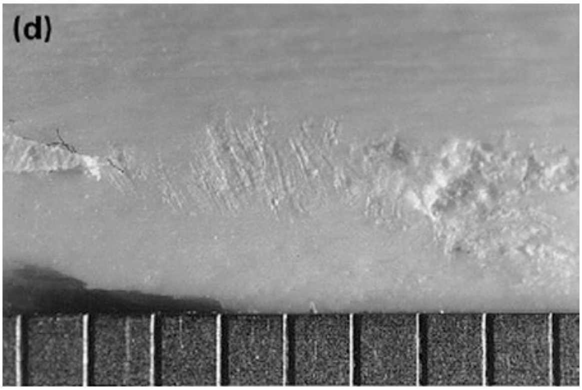

Fig. 14.15 SEM micrograph of anvil percussion pit with diagnostic microstriations leading out of the pit, reflecting the friction of the anvil across the bone surface during impact. Scale: 150 microns. (Micrograph from Blumenschine and Selvaggio (1988:763, Fig. 1c, used with permission of Elsevier)

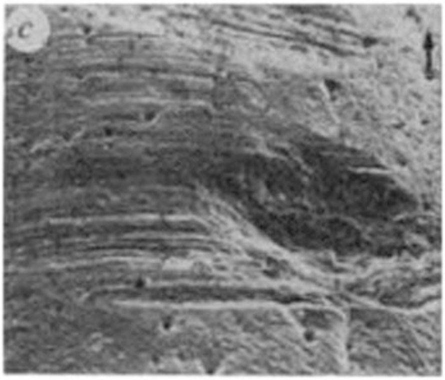

Fig. 14.16 Percussion pit on unmodified bone without striations. Scale: 1 mm (From Galán et al. (2009:783, Fig. 6, used with permission of M. Domínguez-Rodrigo and Elsevier)

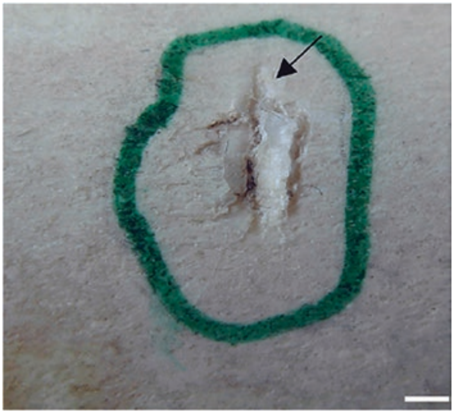

Fig. 14.17 SEM micrograph of jagged surface and striations on deer antler beam, produced by its use as a soft-hammer percussor for stone artifact production by Sandra L. Olsen (1989:132, Fig. 7). Scale: bar is 1000 microns. Compare with Fig. 13.13 for natural antler modification image. (Used with permission of S. L. Olsen and Elsevier)

These were the least common percussion mark in both hammerstone-anvil sets, with pits with associated striations and striae fields being more common. In the smoother hammerstone-anvil experimental set, pits without microstriations are from five to nine times as common as they are with angular hammerstones (a chopper and a polyhedron) and anvils.

Blasco et al. (2014: 1093) report that their batting/clubbing assemblage had percussion pits on 12% of all of fragments, and that most lacked associated microstriations. They state that some, “display similar features to chop-marks,” explaining this by the fact that, “they are also generated by the application of a dynamic and/or percussive force against an angled edge.” Some percussion pits are “variable geometrically shaped marks,” 2–30 mm in maximum dimension.

14.2.5 Clubbing by Bone or Antler Tools

S. L. Olsen’s (1989) actualistic research and application of SEM to specimens established that it was possible to distinguish between modifications to deer antler made during life from those made during the human use of deer antler as percussors in producing stone artifacts. Figure 14.17 shows the jagged and striated surface of an experimental antler percussor used to flake flint, which can be compared to the generally smooth surface of the *in vivo* modifications (Fig. 13.13). Olsen noted that, at high magnification, embedded chips of stone could sometimes be seen in percussors.

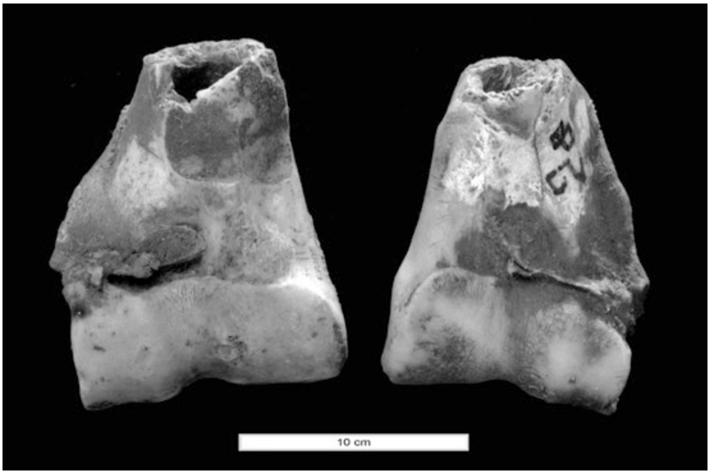

Fig. 14.18 Two common zebra (*Equus quagga boehmi*) distal humeri from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya, showing redundant patterning in transverse fractures at distal shafts, rebound flake scars from an anvil, and abrasion to the break surface, possibly due to ungulate trampling (Photo by Don Harris, of a specimen collected by the author. Reproduced with permission of the Center for the Study of the First Americans, Texas A & M University)

14.2.6 Fracture Outlines

Experimental research has found that hammerstone percussion on fresh bone, with or without anvils, generally results in spiraling fractures of varied lengths and termination forms, depending upon a skeletal element's osteonal organization and the amount of force loaded on the bone cylinder. Smooth break surfaces accompany these break outlines. As noted in Chap. 11, transverse breaks occur when the stress loaded exceeds an element's capacity to transmit strain longitudinally. (Fig. 14.18)

Blasco et al. (2014) report that batting/clubbing percussion produced transverse diaphyseal fractures at more than twice the rate as did hammerstone percussion: 36.7%, compared to 16.6% with hammerstone percussion, and of jagged fracture surfaces: 21.3%, compared to 3.9% (Blasco et al. 2014: 1092). Batting/clubbing produced fewer diaphyseal fragments than did hammerstone percussion. However, diaphysis repeatedly struck against an anvil, multiple bone splinters were driven into the marrow. I suspect that the splintering rate would have decreased with more effective initial strikes, had the experimenters further developed their skills. Blasco et al. (2014) found such a learning curve, though noting that actors with greater body size and strength – some were sports team members – tended to produce fractures more swiftly.

14.3 Problems of "Equifinality"

Chapter 13 discussed the apparent equifinality between marks produced by trampling and cut marks inflicted by stone implements, and how further experimental work has clarified differences between the two, using multiple variables and contextual information (sedimentary matrix). Zooarchaeologists have likewise cautioned about assuming human agency from notches on bones, which cannot only be produced by nonhuman carnivores but also by geological forces. Hammerstone impacts can be perfectly produced on fresh bones by falling rocks in caves (Oliver 1989), and, if such an element were resting on a rocky substrate, such an impact might even produce anvil damage. In this case, the effectors and causal processes are very similar to human dynamic loading, producing virtually identical result.

Very large-toothed carnivores such as modern large cats and hyenas can produce flakes and flake scars by static loading, that is, a form of pressure flaking, as noted in Chap. 11, see Fig. 14.13). Capaldo and Blumenschine (1994) compared experimentally produced hammerstone impact notches with those produced by hyenas and lions on long bones of small-to-medium-sized and large bovids. They determined that hammerstone-produced flakes had more obtuse release angles than did those produced by carnivore teeth. For small to medium-sized bovids, notches produced by hammerstone were broader than those produced by hyena teeth at a statistically significant level, although ranges of the two overlapped. For larger bovids, the same trend was seen, but not at the level of statistical significance. Capaldo and Blumenschine (1994:730) stipulate a conservative definition of percussion flakes:

> …a single bone flake or a nested series of flakes, leaving a negative flake scar that extends through the entire thickness of the bone and onto the medullary surface…. Normal notches, therefore, exclude flake scars on the cortical surface of bone (inverse retouch on lithic artifacts) and indentations emanating from or restricted to the bone thickness. We refer to these latter forms as pseudo notches.

Pickering and Egeland (2006) follow the same definition but argue from their experimental observations that some pseudo notches are definitely percussion products, and that these may be more common on some skeletal elements, such as ruminant radii, than others. They agree with Capaldo and Blumenschine that percussion and carnivore tooth flakes show sufficient overlap that a prudent course is to place them into an ambiguous category. Both sets of researchers and Fisher (1995) suggest that the best way to discern the identity of the actor is to inspect notched specimens for other surface modifications typical of nonhuman carnivores (scores, pits) versus hominin (anvil pits, striations) handling.

In such cases of ambiguity, multiple lines of evidence, such as associated cut or tooth marks or other aspects of physical context, may clarify the effector and actor. This was called a "configurational approach" by Domínguez-Rodrigo et al. (2010) and a "forensic approach" by myself and Lyman (Chap. 3). Nonetheless, analysts should accept that the causes of some modifications might remain ambiguous. In such cases, it is prudent to use descriptive terms for equivocal evidence that do not specify the actor or effector. I have done this working with one taphonomically complex assemblage where sedimentary abrasion has so altered carnivore or human marks on some specimens that I stipulate "indeterminate mechanical damage" as a bone surface modification option.

The next chapter introduces culinary processing and advocates for a *chaîne opératoire* approach to animal carcass processing.

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Chapter 15
Culinary Processing and Preservational Effects on Bone

Most discussions of technology in relation to animals in hominin evolution focus on those of animal *acquisition* – cooperative hunting, projectile weapons, traps, fishing and fowling tools. Less attention has been accorded to uniquely human *processing* technologies and techniques that enhance or extend nutrient availability from animal tissues – earth ovens, stone-boiling, heat-retentive stone and ceramic cooking ovens and vessels, management of fermentation. The latter are equally unique to genus *Homo* and have supported distinctive features human physical and social evolution for over 2 million years.

As used here*, culinary processing* refers to the handling animal tissues for consumption after carcass acquisition and butchery and before consumption. "Culinary processing" is preferable to "cooking" because not all such handling of animal tissues involves the application of heat. Extracting and whipping marrow before consumption, for example is a culinary technique that do not involve heating. With culinary processing, *preservational processing* permits deferred consumption of animal tissues by impeding bacterial decomposition, as in drying meat into jerky or mincing jerky to mix with other ingredients for deferred consumption, or by governing its course, as cheese-making or meat fermentation. Preserved foods can be transferred to consumers outside the immediate social circle of their production as gifts, reciprocal exchanges, or commodities for market.

Chapters 14 and 15 artificially divide the continuum of human animal processing, simply to break up a large body of material into more manageable segments. This chapter actually argues for a *chaîne opératoire* approach that unites primary and secondary butchery with culinary and preservational processing, thereby facilitating functional analysis of the end products that archaeologists analyze. It opens with an evolutionary perspective on technologically aided food preparation. This is followed by discussions of gaps in zooarchaeological knowledge of heat-aided culinary handling. It next presents a case for the use of a *Chaîne opératoire* approach. It then outlines the nutritional advantages of pyrotechnical culinary processing and

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preservational processing, followed by a survey of distinctive signatures of culinary and processing on bone. The chapter ends with a discussion of whether and how culinary processing can be discerned archaeologically.

15.1 Culinary Processing in Evolutionary Perspective

Culinary processing of all types is a kind of "outsourcing" of the digestive process and pre-processing of meat has considerable antiquity in our ancestry. Hammerstone percussion marks and cut marks on two-and-a-half million year-old African ungulate testify to hominin extraction of marrow and removal of muscle, preceding the use of fire by 1–2 million years (Semaw 2000; de Heinzelin et al. 1999). Slicing up raw meat before consumption requires no more than a simple stone flake, and pounding before mastication only involves a hammerstone and anvil.

Heat-aided culinary processing is widely understood to confer evolutionary advantages by enhancing nutrient availability and reducing risk of bacterial and parasitic infection (see 15.4 **Nutrient Gains through Culinary and Preservational Processing**). Less apparent than these is the radical reduction of the time and energy spent on mastication that pre-processing techniques and technology confer on genus *Homo*. Wrangham (2009:139–142) notes that chimpanzees spend on average 6 h a day chewing the raw fruits and leaves comprising their diet, whereas humans spend 0.6–1.2 h a day chewing cooked or otherwise pre-processed foods. The divergence between genus *Homo* and earlier hominins' chewing-related energy expenditure appears to have begun in Africa 1.9–1.8 million years ago, with *Homo erectus*, a species that spread from Africa into temperate western and tropical east Eurasia by 1.7 million. *Homo erectus* fossils present a paradox: their bodies and brains are about 50% larger than those of earlier hominins, which would demand much more energy to maintain, yet their fossils have smaller teeth and osteological evidence for reduced chewing muscles and gut size, compared to those of earlier hominins. Paleoanthropologists agree that these traits testify to a major dietary shift but debate what, specifically, enabled it nearly 2 million years ago. Wrangham (2017) and his coworkers (e.g. Carmody et al. 2011) contend this anatomical transition was enabled by fire-mediated food processing from the very emergence of the *H. erectus* lineage. This assertion is complicated by lack of direct evidence for control of fire before 500,000 years ago. Others have proposed this shift could have been enabled by incorporating substantially more animal foods into the diet before the regular use of fire (Leonard et al. 2007; Ungar et al. 2006), or by new social behaviors facilitating food sharing (Leonard et al. 2007).

Using human lab volunteers, Zink and Lieberman (2016) explored whether technologically aided pre-processing (pounding, slicing,) without heating could reduce the masticatory stresses imposed by the raw diets of foods suggested for pre-*Homo erectus* hominins by dental wear and stable isotope studies: tubers and other roots, or "underground storage organs" (USOs), and meat. Experimental subjects were monitored for the number of chews and the muscular force exerted while chewing varied samples until the subject felt ready to swallow. They then spat out the chewed bolus, each of which was assessed for particle size and structure. Pre-processing trials were first done with raw USOs and meat, presented in unmodified chunks, pounded, and sliced forms. Outcomes were compared to those of trials using cooked USOs and meat in the same forms. Zink and Lieberman found that slicing raw meat improved subjects' ability to chew it into smaller particles, being on average 41%, more efficient than pounding. For raw USOs, pounding was more efficient than slicing and would have reduced the number of chews per year by 5% and simultaneously lowering mastication force demands by 12%. Zink and Lieberman argue that increasing (sliced) raw meat consumption could have significantly reduced *Homo erectus* chewing cycles per year, estimating that increasing meat to one-third of dietary intake diet would have reduced chews by 13% and masticatory force exerted by 15%. Such a proportion of meat in the *Homo erectus* diet is probably unrealistically high, even considering scavenging and hunting together as sources of animal foods. However, the experiment showed that non-pyrotechnical food processing with simple tools confers a significant reduction in the time and energy spent processing food.

One hint that that pre-cooking meat processing and consumption could have existed in significant levels was reviewed in Chap. 5: the zoonotic transfer of *Taenia simbae* from the large African carnivore – ungulate cycle into hominins, where it evolved into *T. saginata* and *T. asiatica* (Hoberg et al. 2001). *Taenia* genomics estimates this occurred about 1.7 million years ago, coinciding with the first few hundred thousand years of *H. erectus*' existence. Eating an increased amount of raw ungulate meat would have facilitated the entrenchment of this tapeworm into *H. erectus*.

15.2 Gaps in Zooarchaeological Studies of Bone Modification

Because the nutritional benefits offsetting animal acquisition costs are nearly always realized in the context of culinary handling, this area should be an area of considerable interest in studies of animal use by ancient and modern hominins. However, zooarchaeological research on cut mark and bone fracture patterning has preponderantly involved raw carcasses and bones. This probably a reasonable focus for those studying very early hominins, but most archaeofaunal samples younger than 450,000 years were produced by fire wielding hominins (Attwell et al. 2015).

Why does raw versus cooked bone matter? Heat-aided culinary processing can affect bone modifications and frequencies in three ways:

1. Heating shortens collagen fibrils in bone, decreasing elements' resilience under dynamic loading and other stresses, producing different fracture outlines and break surface textures from those in uncooked bone.
2. Heating gelatinizes the collagen fibers in connective tissues, reducing the need for cutting edge to remove muscle from bones. Skeletal elements in carcass

segments cooked “bone-in” may therefore diverge in cut mark rates from the same elements from which raw muscles were removed.

3. Cooking can “reset” the relative nutritive value of body segments compared to their value when raw, resulting in revised decisions about transport versus discard. The advent of cooking technologies could thus alter skeletal element frequencies in transported versus discarded assemblages (Chap. 19). Lupo and Schmitt (1997) report experimental data that suggest a shift in handling vertebrae, which have costs of stripping meat when raw that exceed those of transporting the unstripped segments to base for cooking and easier defleshing.

It is possible that some of the variation in cut mark frequencies on cervid bones reported by Lyman (1995) could result from situational differences in body segment cooking methods, which in turn would have altered the likelihood that cuts would be inflicted. This may be difficult to assess empirically but it is worth exploring with bone color shifts and changes in surface texture, fracture outlines, and break surface texture typical of thermal stress (see Sect. 15.6 below).

Why is our knowledge of raw carcass and bone handling greater than that of cooked carcasses and elements? Paleoanthropological researchers have strongly influenced the last 40 years’ zooarchaeological methods, as have studies of mass-processing herd-living ruminants. These include research on prehistoric bison kills (e.g. Frison 1974; Wheat 1972) and Binford‘s (1978, 1981) actualistic butchery research with Nunamiut people, who obtained over 90% of their sustenance from hunting migratory caribou herds. Mass kills challenge butchers to recover as much from raw carcasses as possible over a short time span, and processing efficiencies approach those of industrial mass production. Mass processing is actually exceptional among most hunting peoples. Ethnoarchaeological research shows most hunting peoples kill a single large animal at a time and at a steadier rate through the year (Bunn 1993; O’Connell et al. 1990; Bartram et al. 1991; O’Connell and Marshall 1989). Chapters 19 and 20 will show that such hunters are often motivated to transport an entire carcass, albeit in parts, from the acquisition locale to a home base for further processing and consumption (Emerson 1993; Lupo 2006). Initial processing and transport decisions are made during primary and secondary butchery when carcasses may be raw. These are influenced by many factors (Chap. 19) including *a priori* knowledge of intended culinary or preservational tactics (Gifford-Gonzalez 1989). Groups with domestic animals slaughter them near where they will be consumed, reducing but not eliminating selective discard (Chap. 19).

Some decades ago, motivated by some “unusual” fracture patterns in an ethnoarchaeological assemblage that I had not directly observed being created – which we now know are breaks on heat-stressed elements – I encountered the lack of investigations on heat-aided bone processing (Gifford-Gonzalez 1993). At that point, the most systematic research on culinary bone modification was that done on human cannibalism (e.g. White 1992), begging the question of why this analytic area had been so weakly developed in zooarchaeology. Besides crediting the factors noted above, I asked whether the raw bone focus might also stem from zooarchaeologists’ unconscious privileging of animal acquisition and a reciprocal devaluation of culinary activities, which are culturally gendered activities (see also Montón Subias 2002; Bosch et al. 2011). I noted that, with the exception of Binford (1978) and Yellen (1977) – I would now include Oliver (1993) – even ethnoarchaeological research, including my own, has stinted on deliberate attention to the outcomes of culinary processing. The same question was raised about 20 years later by Graff and Rodríguez-Alegría (2012), in relation to "the menial art of cooking" in archaeology, with an interesting discussion of reasons why. I argued that the problem with researchers' cultural stereotypes that divert attention away from this energetically critical end-stage of food processing is not one of "political incorrectness." The problem is that they produce methodologically flawed analyses. Since then, a number of researchers have advanced understandings of heat-aided culinary processing and its effects on bone, as ensuing sections will attest.

15.3 Vertebrate Bodies, Behavioral Chains, *Chaîne Opératoires*

Binford (1977) stressed that vertebrate bodies present consistent challenges to human consumers, from primary and secondary butchery through further processing operations. Lyman (1987) and O'Connor (1993) reiterated Binford's (1978) point that butchery is not an event but rather a *process*, being a series of acts in a continuum of operations from acquisition of a vertebrate body to post-consumption discard of its bony remnants. Processing and consuming animal bodies requires that tasks be accomplished in a somewhat fixed order – some actions must by necessity precede others. This principle is at the core of Schiffer's (1987) concept of the behavioral chain, Americanist lithic technology studies' "reduction sequence" (Andrefsky 2005), and the *chaîne opératoire*, or operational chain, approach developed in European lithic studies (Lemonnier 1986; Pelegrin et al. 1988), which had also been employed in ceramic analysis (e.g. Habicht-Mauche 2006; Vitelli 2007).

In any given *chaîne opératoire*, some operations cannot be undertaken until others have been accomplished. Knowledge of such sequences derives from prior observations of the material properties and the sequences of operation employed to produce final forms, whether a bifacial stone tool, a ceramic vessel, or a bronze axe head. Each case depends upon the inherently uniform properties of specific material to build expectations about the temporal sequence of operations people must undertake to produce a final product (Gifford-Gonzalez 2008).

These approaches are intrinsically *product-focused*. They generate expectations about the nature and temporal order of processing activities, hallmarks of those stages, and even contexts of the work accomplished in each stage. For example, unsmelted ore, slag, and a finished cast iron hoe blade testify to different stages in the *chaîne opératoire* of iron artifact production. All may not originally occur in the same spatial contexts – e.g. the ore originates in a mining operation, the slag at a smelter location, the finished hoe at a smithy.

Applying the *chaîne opératoire* approach to carcass processing integrates butchery, preservational processing, meal preparation, consumption, and discard operations. Because it is a product-focused approach, it can generate expectations about the *sequence* of human actions on the "raw material" of vertebrate bodies. It approaches modifications to bone as a time-sequenced order, governed in part by anatomy, in part by available tools (Seetah 2008), and in part by the cultural and socially structured choices by the actors involved. It creates expectations about the signatures of sequential processing episodes and to some extent helps define the possible variety of localities at which specific operations can occur. This framework permits zooarchaeologists to ask what stage or stages in a carcass handling sequence are represented in a given sample. To give a concrete example, in tetrapod vertebrates it is virtually impossible to inflict cuts on the ventral surfaces of the ribs and thoracic vertebrae before the rib cage is opened, and the thoracic viscera are removed. Consistent appearance of cut marks on the ventral surfaces of archaeofaunal specimens thus testifies not only to the infliction of cut marks but also, by logical extension, to prior stages in the chain of operations upon an animal carcass, such as extraction of the viscera, which may itself leave no direct evidence. With knowledge of the specific constraints offered by an animal species' anatomy – processing a salmon will differ from processing a sheep – a detailed scenario for such an operational chain can be developed to guide analysis.

In 1993, in the manner of simultaneous inventions, O'Connor (1993) and I (Gifford-Gonzalez 1993), used flow-charts to propose that butchery should be viewed as a sequence of operations producing more or less predictable outcomes. Sadly, we did not immediately convert the entire English-speaking zooarchaeological world to our way of thinking. A decade later, in his critical assessment of the gaps in archaeological study of forager culinary practices, Miracle (2002:67) argued that studies of ancient food and consumption would benefit from a *chaîne opératoire* approach because, "food is material culture created by technical and social acts," further noting:

> The productive and consumptive activities of an individual actor are series of decisions, each historically contingent (to some extent dependent on prior decisions or existing constraints), but always, selected from a range of alternatives.

Seetah (2008) reiterated the call to view butchery as a form of *chaîne opératoire* that begins with an entire animal and ends with meals and other useful products.

Figure 15.1 presents a simple model of the chain of human *actions* affecting an animal carcass in a hunting system, and of the material *modifications* and *discards* that those actions produce. It assumes prey are usually acquired at a distance from the locality to which hunters ultimately return. It does not predict conditions under which various carcass parts may be transported or abandoned (O'Connell et al. 1988, 1990). Such a model creates expectations concerning the *possible products* of each *sequential phase* in the chain of carcass processing. It shows the movement of animal bodies in space as well as through time and uses the term "locale," rather than "site," to denote places where specific processing operations occur. This aims to maintain the distinction between the *places* where human activities occur in a landscape and the *archaeological entities* formed by those activities' material

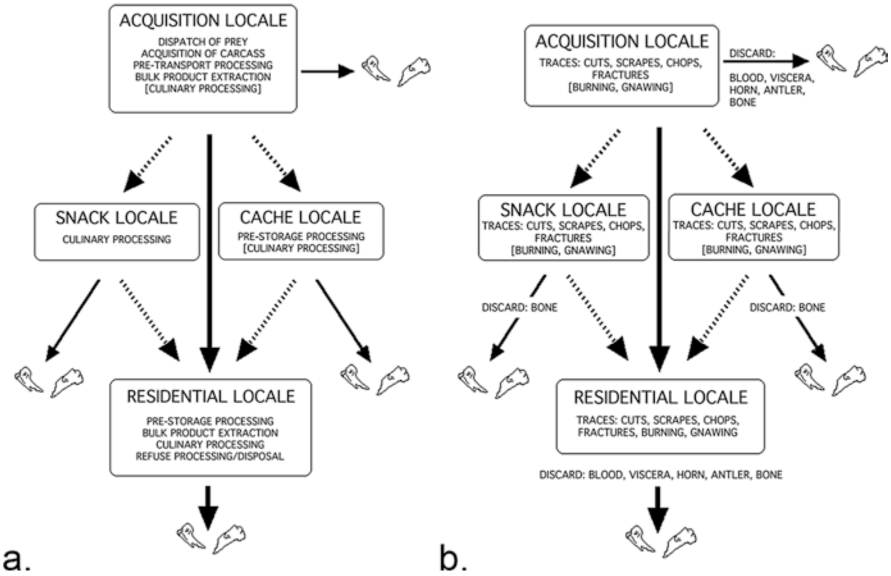

Fig. 15.1 A product-focused approach to following the flow of vertebrates as food, from whole carcass to debris, here exemplified by large hunted prey. (**a**) Frequently occurring locations of acquisition and processing, with expectations of handling occurring at each stage. (**b**) Traces expected to be produced by the handling tactics at each locality (Illustration by author, redrawn after Gifford-Gonzalez (1993:191, 192, Figs. 11.1, 11.2, and 11.3), with permission of Southern Illinois University Press)

by-products and other processes. Schiffer (1987), Binford (1980) and others have noted that archaeological sites are not occupied, they are formed. The operational chain represented in Fig. 15.1 does not collapse these categories because some processing locales may leave few archaeologically visible traces ("sites"), but their existence may indirectly be reflected by attributes of specimens that passed through them and accumulated at another locale. Figure 15.2 shows a similar flow of operations and material effects in a pastoralist system that I have found useful for organizing my thinking about sites documented during ethnoarchaeological research with Dassanetch agropastoralists in northern Kenya. It could also be modified for smaller-scale use of livestock in farming systems. The final stages in this chain of operations reap the nutritional gains of animal acquisition, and these will be dealt with in the next section.

15.3.1 Functional Inferences from Cut Mark Placement

The *chaîne opératoire* approach to carcass processing would benefit from any functional interpretations of bone surface modifications that could testify to a stage or stages of the process. However, this has proved more challenging than once hoped.

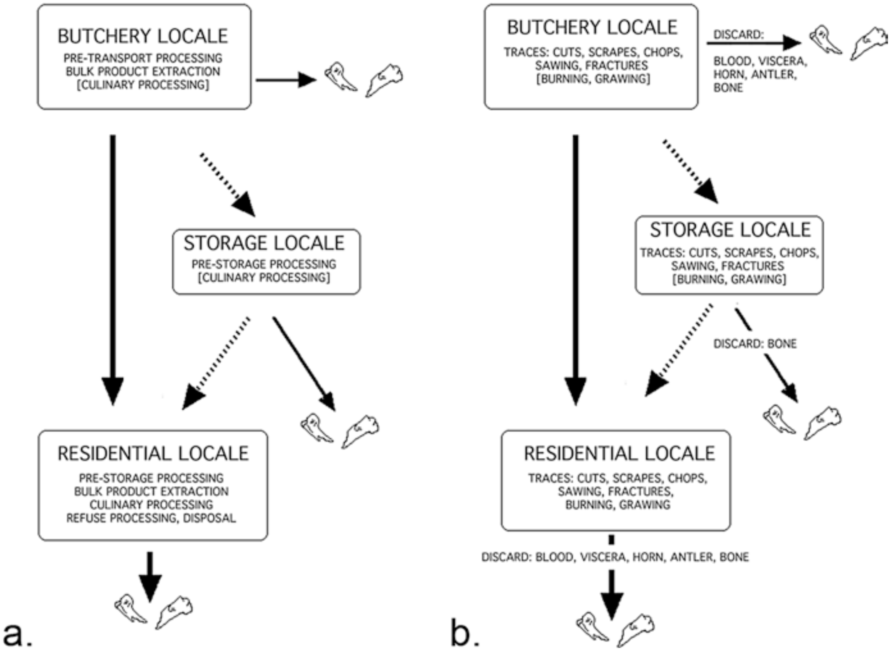

Fig. 15.2 A product-focused approach to following the flow of vertebrates as food, from whole carcass to debris, here exemplified by large domestic prey. (**a**) Common locations of acquisition and processing, with expectations of handling occurring at each stage. (**b**) Traces expected to be produced by the handling tactics at each locality (After Gifford-Gonzalez (1993:193, Figs. 11.1, 11.2, and 11.3), with permission of Southern Illinois University Press)

Cut marks (Chap. 14) can sometimes be read for their functional meaning, but Lyman's caution about their epiphenomenal nature, as well as their situational variability, should be kept in mind. Binford (1981) published an illustrated list of cut and chop marks on caribou skeletal elements processed by Nunamiut people, ascribing each the immediate functional goals: skinning, dismemberment, and defleshing (his "filleting"). His ultimate goal was to build a "dictionary" for inferring similar, functionally oriented behavior from archaeofaunal evidence. Binford acknowledged that this work built on that of Guilday et al. (1962). His approach also followed in the footsteps of Frison and coworkers, who had for some time been inferring the sequence and functional meaning of butchery marks in North American bison kill sites (e.g. Frison and Reher 1970; see also Frison and Todd 1987). Binford's coding system for each mark described its location on a skeletal element that did not impute an intention or goal. However, his illustrations grouped marks according to their function, with cuts on the scapula that he associated with dismemberment illustrated separately from those associated with meat removal (Fig. 15.3).

Some zooarchaeologists began to use Binford's 1981 functional attributions of cut marks to infer the nature of butchery operations undertaken at specific sites. Others contested, amplified, or attempted to systematize cut mark descriptions.

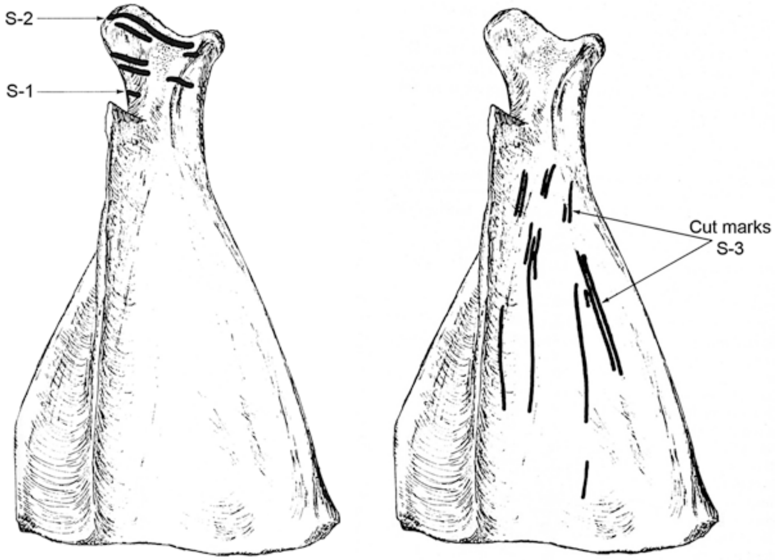

Fig. 15.3 Binford's examples of cut mark placement on the scapula for dismemberment (left) and defleshing (right) (From Binford (1981:98, 122, Figs. 4.6 and 4.29). Used with permission of Estate of Lewis R. Binford and Elsevier/Academic Press)

Many noted that Binford represented cuts only on epiphyseal ends of long bones, while many cut marks associated with flesh removal are on diaphyses (Marean 1998; Blumenschine 1988; Egeland et al. 2004). Thus, Binford's descriptive system omitted the variation produced by divergent tactics of dismemberment and meat removal, falling short of the "uniformitarian" dictionary he'd hoped to produce. Lyman (1987) proposed a numerically coded system to describe the location, orientation, and nature of cuts and other modifications to bone, which could be used in computer data manipulation. I argued that it is best to retain a focus on the soft tissues (muscles, tendons, ligaments) severed, because similar cutting edge interventions can accomplish different goals (Gifford-Gonzalez 1989). For example, the ruminant artiodactyl elbow joint is so tightly buttressed by bone and connective tissue as to prevent dismemberment by simple, transverse cutting. Butchers lacking metal chopping tools may open the inner side of the elbow joint by severing the biceps brachii muscles inserting on the palmar side of the radioulna. This exposed the inner joint for leverage and dislocation. So, although cuts around the biceps muscle insertion on the radius are technically "defleshing" marks, here, they are functionally implicated in dismemberment. Frison et al. (e.g. Frison and Reher 1970) had in fact been describing soft tissues severed by their anatomical names and inferring sequence and function *after* the aggregate of evidence is assessed in light of the knowledge of operations dictated by bison or other artiodactyl anatomy. This approach parallels the longstanding tradition of forensic anthropology and pathology forensic investigators.

It is useful to summarize a few generally agreed upon points regarding the placement and intensity of cuts on skeletal elements and what they tell us about handling. This outline should be read while bearing in mind Lyman's cautions about cut marks as epiphenomena (Chap. 14).

1. Barring the use of metal chopping tools, dismemberment by cutting and chopping usually focuses at or immediately adjacent to the joints of the skeleton (Chap. 19).
2. Removing muscle from long bones often leaves cut marks on diaphyseal surfaces. Mid-shaft cut marks are inflicted when the connective tissue (fascia) that covers muscles and attaches to the periosteum, are repeatedly "snipped" to remove the flesh from the bone.
   a. Dissection class instructors encourage separating fascial attachments manually blunt dissection, using knuckles or the side of the hand to force connective tissues apart. Muscles can be separated from the skin and periosteum with minimal cutting, even in larger animals.
   b. Refraining from cutting avoids breaching fascial "wrappers" of muscles removed, protecting the meat from bacterial and other contamination.
   c. With smaller prey such as rabbits, much muscle removal can be accomplished by hand. Larger-bodied animals require cutting some muscle origins and insertions.
3. Disparate approaches to skinning may be applied when the aim is to remove an entire skin for other uses, as outlined by Binford (1981:106–107).
4. Historic archaeologists note that some body segments used in roasts (with shoulder, pelvic, upper long bones) often display long cut marks, or carving marks, inflicted while portioning a cooked roast (e.g. Crader 1984), a serving style that emerged in the eighteenth century (Deetz 1996).

The next section deals exclusively with heat-aided techniques because non-pyrotechnical meat processing has previously been reviewed in this chapter.

15.4 Nutrient Gains Through Culinary and Preservational Processing

Heating *denatures* protein by weakening its component amino acids' internal bonds, opening their molecular structure to digestive enzymes. Cooking at 40–60 °C (104–140 °F) denatures meat protein, making it more digestible, while cooking at over 65 °C (150 °F) gelatinizes connective tissues' collagen fibers in and around muscles, rendering the meat very tender (Wandsnider 1997). Heating to 65–70 °C (150–178 °F) also kills bacteria and parasites in meat.

In heat-based handling, different artifacts and techniques produce divergent concentrations of retrievable nutrients. Table 15.1 shows the nutrient yields two widely

Table 15.1 Comparison of protein and total lipid yields of various cuts of domestic animal meats in raw, braised (container-cooked), and broiled types of cooking treatment (USDA Agricultural Research Service 2008)

Cut of meat and treatment	Protein (g/100 g)	% Change	∑ lipid (g/100 g)	% Change
Beef, top round				
Raw	21.5	–	9.4	–
Broiled (equivalent to roasting)	30.2	+40%	9.6	+3%
Braised (equivalent to boiling)	33.8	+57%	11.4	+22%
Pork, boneless sirloin				
Raw	20.6	–	6.3	–
Broiled (equivalent to roasting)	30.5	+48%	8.4	+33%
Braised (equivalent to boiling)	26.5	+29%	8.6	+36%
Pork loin, rib, bone-in				
Raw	20.2	–	13.6	–
Broiled (equivalent to roasting)	28.8	+43%	15.5	14%
Braised (equivalent to boiling)	26.7	+32%	15.1	11%
Lamb, leg & shoulder, cubed				
Raw	20.2	–	5.3	–
Broiled (equivalent to roasting)	28.1	+39%	7.3	+39%
Braised (equivalent to boiling)	33.7	+67%	8.8	+67%
Lamb, whole shoulder				
Raw	16.6	–	21.5	–
Broiled (equivalent to roasting)	24.4	+47%	19.3	−10%
Braised (equivalent to boiling)	28.7	+73%	24.6	+14%

used modern cooking methods: *broiling*, roughly equivalent to roasting near a fire, and *braising*, roughly equivalent to pot boiling. Heating drives off the water from meats, concentrating the remaining protein, increasing its digestibility, and retarding spoilage. Broiling in an oven broiler captures hot liquid fats and other fluids in a pan for use in sauces. However, those who barbecue know that meat exposed to an open fire loses these fluids, as they drip into the fire or to the ground. Braising entails browning and cooking meat in a container, capturing the fat and other fluids released during cooking; it differs from stewing only in that it does not add water to the juices from the meat. Table 15.1 shows that container-based cooking generally captures more lipids and yields more available proteins; roasting pork appears to produce more lipids than braising, but this counts the fluids captured in a metal pan, unlikely in pre-ceramic and metallurgic eras. Gains in ease of digestibility and lipid capture confer significant advantages on lactating females and younger children with developing nervous systems (Chap. 5, Leonard et al. 2007; Speth and Spielmann 1983). This may account for the widespread adoption of ceramic and metal containers, even by mobile foragers, in prehistoric and historic times.

Wandsnider (1997) discusses traditional techniques and technologies for processing animals with varying proportions of collagen fibers to muscle and proportions of fat to lean meat. In the first case, she states:

> Muscle with little collagen, such as that attached to the dorsal portion of the spine on a large quadruped, needs only a *brief exposure to moderate temperatures;* broiling, pan-frying, and roasting suffice in this case. When more connective tissue is present, as will be true for most carcasses of wild species, *longer exposure to moist heat* is needed to convert the collagen to gelatin; i.e., braising and stewing is recommended…(Wandsnider 1997:10).

Ethnographies attest to consistently different cooking techniques applied to cuts with differing proportions of fat to protein (Wandsnider 1997:12–14):

1. Species with low lipid to protein ratios were prepared by boiling, as were dried meats.
2. Meats from species with low lipid to protein ratios and slightly less lean species may be roasted for under an hour in ash, hot sand, or over coals.
3. Meats with relatively high lipid to protein ratios were moist-cooked, especially pit roasted.

We associate techniques for handling meat with metal technology – frying pans, cooking pots, stove ovens – but counterparts for these can be found in non-metallurgical, and even non-ceramic technologies. Roasting is done over or near open flame (Fig. 15.4a). Boiling (Fig. 15.4b) can be accomplished by placing heated rocks into tightly woven baskets, hide vessels, or pits lined with clay or hides (Thoms 2008, 2009). Alternatively, stone containers can be preheated in fires for cooking moist foods by remnant heat. Moist heat can be applied using closed containers (the "Dutch oven" technique), by encasing a whole animal or segment in clay and baking it in embers, or pit roasting – with the pit actually being a very large closed container. The latter is an efficient means of cooking large amounts of fatty meat, simultaneously tenderizing the muscle and capturing rendered fat and drippings with plant foods included in the leaf or hide wrapping.

Wandsnider's (1997) ethnographic survey reported that pit roasting of wild animals was seasonal, timed to when the prey were fattest. Very large animals – bison, bears, and pigs – were cooked nearly 24 h. She hypothesized that such prolonged heat treatment would have shortened fatty acid chains via lipid hydrolysis, promoting digestibility by hunting peoples unaccustomed to fatty foods. These ethnographies also testify that pit roasting depended on coordinated labor, often from several households, and it frequently involved feasting.

15.4.1 Marrow Cooking Before Extraction

Oliver (1993) and I (Gifford-Gonzalez 1989) reported roasting of meat-stripped long bones of large ungulates by Hadza foragers and Dassanetch agropastoralists as a method of cooking marrow before consumption, and Yellen (personal communication, 1988) also observed marrow cooking during from his ethnoarchaeological work with !Kung foragers. Hadza individuals placed defleshed long bones of larger ungulates directly in embers of a fire, set them aside to cool, and cracked them open by percussion to extract marrow (Oliver 1993). Exposure to heat shrinks the

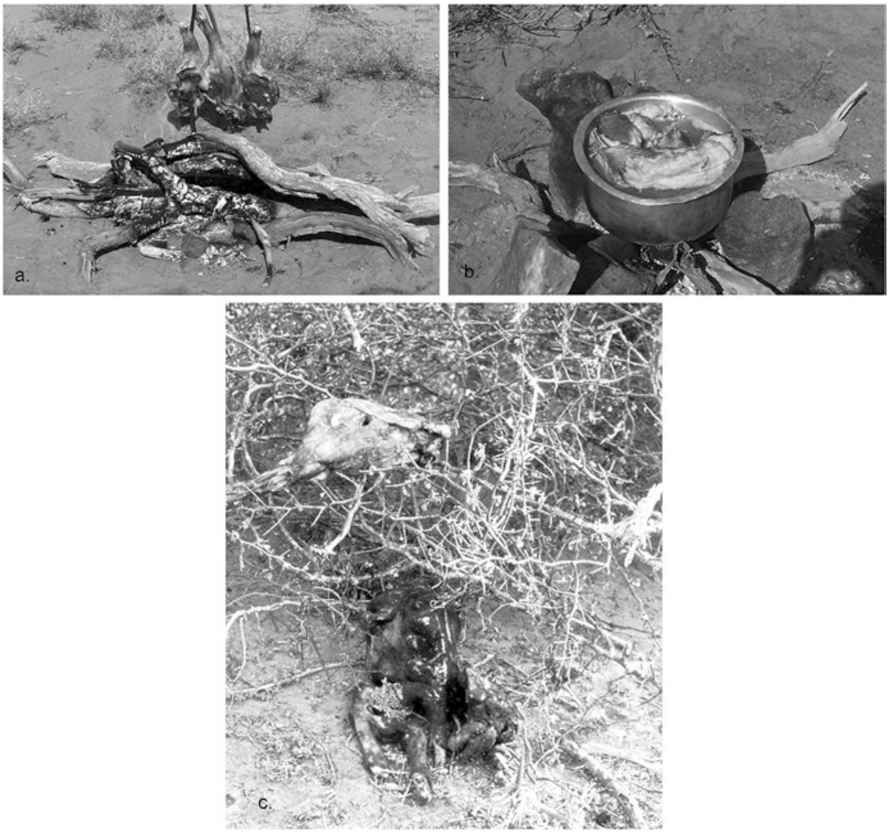

Fig. 15.4 One sheep, three modes of culinary processing, and three types of thermal alteration. (**a**) roasting limb units, with bones of distal ends directly exposed to thermal stress, traditional "food for men" among the Kenyan Dassanetch; (**b**) boiling fatty lumbar and sacral spine, plus heart and other fatty entrails, traditional "food for women" among the Dassanetch; (**c**). singed head, metacarpal- and metatarsal-to-toe units on ground, awaiting scraping of charred skin and cracking to extract within-bone nutrients, bones directly and heavily exposed to thermal stress, consumed by both genders and all ages. Note roasted limb segment stored in tree branches above. (Photos by the author)

endosteal lining of marrow cavities around the marrow, producing smaller, more readily removed billets of cooked fat. Oliver notes that marrow from smaller ungulates was often consumed raw in the field or liberated by cracking and boiling in cooking pots at camp. Long bones broken after such direct heating have transverse fracture outlines and rougher break surface textures (Chap. 11).

15.4.2 Bone Pounding and Consumption

Oliver (1993) reported that Hadza foragers pounded and consumed hemopoetic tissues in cancellous articular ends of long bones. This practice, as well as chewing the cancellous ends of smaller bones, may have been more widespread than once credited in the literature (Chap. 12).

15.5 Preservational Processing and Storage of Animal Products

Preservation and storage of animal products is so widespread among anatomically modern hunter-gatherers and food producers as to seem a normal facet of the human life. However, food storage are unique to the genus *Homo* and was critical to human colonization of high latitudes with restricted growing seasons. Storage can only emerge and be sustained as an adaptive feature when all members of a local and regional population tacitly consent to resource sequestering at the household or foraging group level. Such conditions are absent among common chimpanzees, where dominant animals appropriate animal prey and favored plant foods from lower ranking animals. Thus, storage typical of human societies rests not only on technological innovations but also on a distinctive "social contract," which history tells us is breached in times of societal disruption.

It's possible to view the practical aspects of preservational processing as one end of the culinary processing continuum, since cooking itself retards spoilage and extends the use-life of meat and other animal products, if only for a few days. However, maintaining this distinction may facilitate zooarchaeological study of the emergence of food storage. Lest one assume food storage is strictly the province of farmers and pastoralists, Stopp (2002) detailed Labrador Inuit peoples' storage and preservation tactics, including drying and smoking fish and mammal meat, dehydrating blood and semi-digested lichen from caribou stomachs to be rehydrated and drunk as an infusion by traveling hunters, and fermenting seal oil and caribou blood. Households and co-residing domestic groups produced and accessed preserved foods for their own use or for exchange.

Common preservational methods are:

1. **Slicing meat and sun drying it, or smoking it over fires**. This is applicable at primary or secondary butchery locales and later in processing. It extends meat's use-life, and by evaporating off water, reduces meat weight to be transported (Chap. 19).
2. **Freezing or deep cooling carcass segments**. In high latitudes, hunters and farmers use freezing temperatures to store prey (Binford 1978). This is applied at primary or secondary butchery locales and in later preservational processing. Before artificial refrigeration, farm animals were slaughtered just as the cold

season began (Bowen 1988). Yellow marrow was extracted raw at mass kills and cold stored to be mixed with lean meats over the winter months (Enloe 1993).

3. **Bone grease extraction.** Grease rendering is undertaken using bones of multiple animals with high bone grease levels. Bones from which marrow and meat have been removed are broken into smaller fragments and simmered in a container until fat coalesces on top of the water, when it is skimmed off and stored for consumption with lean meat.
4. **Blood coagulation.** Coagulation can be employed for immediate consumption through simple passive means, as do East African pastoralists who eat clotted blood "puddings." Cooked and denatured blood is often used as a binder for meat and fat scraps in sausages of stuffed intestines, which are preserved by boiling, drying, smoking, or stored after cooking in vegetable oil. Such storage strategies will probably leave few definitive archaeological traces but should be borne in mind as a food processing option, even in non-agricultural contexts.
5. **Management of milk and meat fermentation.** Like 3., fermentation can serve both culinary and preservational ends. Persons who do not produce lactase can more readily digest heated and fermented milk products than they can non-fermented ones. These storage strategies will probably leave few definitive archaeological traces but dairying will affect the living age structure, and thus the mortality structure, of managed herds (Chap. 22).

Stored bone marrow, bone grease, and dairy products extend the time span over which EFA's extracted from animals in peak condition can be consumed by those most in need of them year round, and lean animals can be consumed for their protein with the aid of stored fats (Chap. 5).

The history of dairying in Eurasia has been revolutionized by stable carbon isotope characterization of lipid residues in the fabric of ceramic containers (Copley et al. 2005a, b, c). This has enabled discerning milk fats and also other animal body fats: the adipose tissue signature of pigs can be distinguished from that of ruminants, and both of these from that of horses.

15.6 Diagnostic Traces of Culinary and Preservational Processing

Bone modifications inflicted during food preparation and preservation resemble those made during primary and secondary butchery, necessitating sound arguments from multiple lines of osteological and contextual evidence to make a case for their association with culinary or preservational practices, A *chaîne opératoire* approach provides a framework for reading the aggregate pattern of modifications on specimens as products of a structured sequence, from which can be generated expectations about the stages in a sequence of behaviors when bone surface and fracture modifications could have occurred. Although cooked sections of vertebrate bodies may be readily defleshed with minimal further cutting, the sawing, chopping, and cutting marks associated with primary butchery and other pre-culinary dismemberment will remain on cooked specimens. These, plus signs of thermal stress (*15.6.2 Thermal Alteration: Color, Bone Surface Changes, Bone Fracture Patterns* below), pot boiling (*15.6.6 Evidence of Pot Boiling: Pot-sizing, Pot-Polish* below), and even human chewing marks can elucidate the chain of operations that carcass parts underwent.

Rough specification of a chain of operations from faunal evidence in turn enables recruitment of other, independent lines of evidence – artifactual, architectural, spatial – that could more closely specify the most likely contexts of production (O'Connor 1993; Seetah 2008). This in turn could facilitate consideration of the *locales* and *personnel* involved in the spatial and social dimensions of vertebrate processing (Gifford-Gonzalez 1993; Miracle 2002).

15.6.1 Cut Mark Placement

Cut mark placement related to primary and secondary butchery of uncooked bone has been discussed earlier. When segments of the axial skeleton or limbs are thoroughly cooked, subsequent dismemberment and meat removal can proceed with little cutting tool intervention, simply using with hands or teeth. Bone cooked in body segments and later dismembered and defleshed offers fewer opportunities for a functional reading of cut mark patterning. However, comparative experimental analyses of cutting edge marks on similar skeletal element assemblages subjected to raw butchery and to defleshing after roasting and boiling is, so far as I know, not been done.

15.6.2 Thermal Alteration: Color

Heat can modify vertebrate skeletal elements during cooking, during some forms of refuse disposal, or in cases where a hearth is built on deposits containing them. Naturally occurring fires can also modify bones on land surfaces, in caves or rock shelters, whether or not humans initially handled the bones. Analysts seeking to infer human behavior from thermal alteration of bone face equifinality issues paralleling those of cuts versus trample marks (Chap. 14). As with the former, inferring the probable source of thermal alteration requires systematically examining them and their contexts. One can assess whether thermal alterations display redundant locations on portions of elements that are logical in terms of bone-in cooking techniques (see below) and whether the specimens' archaeological context suggests intentional human application of heat.

Zooarchaeologists' interest in thermal bone modification overlap with those of forensic scientists, who have conducted considerable experimental work in this area, summarized by Fairgrieve (2008). Zooarchaeological and forensic research

Table 15.2 Temperatures at which color change transitions occur in mammalian bone. Overlapping temperature ranges reflect the statistical nature of color transitions of experimental specimens under thermal stress

Temperature °C	Color	References
20 ≤ 285	Neutral white, pale yellow, yellow	(Shipman et al. 1984)
285–525	Brown, reddish brown, very dark grey-brown	(Gejvall 1969; Shipman et al. 1984; Fairgrieve 2008)
300	Black (cortical bone)	(Holden et al. 1995b)
600	Gray, gray-blue	(Holden et al. 1995b)
1000–1200	White	(Holden et al. 1995b)

indicate that bone exposed to fire or high heat (as in an oven) changes color in generally predictable ways. Bone covered with flesh is less likely to display such color shifts than is bone directly exposed to heat. Because soft tissues shrink during cooking, elements at ends of body segment, prominent processes of elements, or sections of elements close to the skin are most likely to be heat stressed.

Most zooarchaeologists know that bone subjected to high heating turns color as its organic component oxidizes, however, ascribing color shifts in archaeofaunal bone to thermal stress requires caution. Some minerals that penetrate bone during diagenesis can mimic colors developed by heating. Shahack-Gross et al. (1997) applied Fourier transform infrared (FTIR) spectroscopy to differentiate Hayonim Cave specimens burned black from those blackened by manganese oxide deposits. The spectrographic analysis also identified some specimens that were both burned and manganese stained. Shipman et al. (1984) also noted that thermal color changes could be overprinted by diagenetic staining.

Shipman et al. (1984) experimented with heating fresh mammal bone without protection of soft tissues, documenting color shifts and using SEM to monitor structural changes in bioapatite. Color shifts initially manifested as partial browning, advanced to deep brown and black, then changed to blue-gray and finally white. Shipman et al. cautioned that these color shifts do not develop at the same temperatures in all bone specimens in their sample, instead undergoing color changes best described statistically. Experiments with human bone by Holden et al. (1995a, b) more firmly established temperature ranges at which color shifts and microscopic changes in collagen and bone apatite occurred. Their correlation of color shifts with temperature ranges is much the same as observed by Shipman et al., with minor changes. Holden et al. used only one skeletal element, the femur, and one species, humans, which may account for the tighter clustering of temperatures and color changes in their results. Table 15.2 summarizes the color shifts and the temperature ranges they occur, from these and other experiments.

Holden et al. (1995a, b) and Fairgrieve (2008) stress that observed color changes result from the *bone's* temperature and not that of surrounding air or matrix. Bone can reach a high temperature by being exposed to a high temperature over a short period, or by being accumulating an incremental heat load that it cannot disperse while being exposed to lower ambient temperatures. The cumulative thermal stress of a specimen's highest temperature governs its color changes. Therefore, a specimen's color only indicates that it reached a given temperature range, not the specific temperature levels under which this occurred.

Blackening of bone is often called carbonization in the literature, referring to the consumption of the organic component of bone, while calcination refers to the gray-through-white color shifts associated with major crystal structure reorganization of bioapatite (e.g. Fairgrieve 2008; Stiner et al. 1995).

For zooarchaeologists, the key finding of such experimental research is that the color shifts and ultrastructural changes discerned by SEM occur at *much higher* temperatures than those ranges involved in roasting or boiling meat (Table 15.2). Water boils at 100 °C (212 °F). Roasts are seldom cooked at more than 175–345° (350–400 °F). The color shift to partial browning begins around 285 °C (545 °F), a higher temperature than any standard oven settings. Exceptions are bone portions exposed directly to heat during roasting, which can accumulate heat as outlined above and undergo color shifts.

Given the persistent problem of inferring cooking from bone condition, and the understanding that boiled bones lack perceptible color shifts, several researchers have explored alternative avenues for distinguishing thermal alteration to bone. Shipman et al. (1984) noted changes in crystal structure and X-ray diffraction properties of bone heated to high temperatures and explored whether X-ray diffraction could distinguish thermally stressed bones that had been subjected to lower temperatures, such as would the case with boiled bone. They subjected a sample of European Mesolithic specimens lacking any color shifts to SEM examination, which indicated that the specimens possessed hydroxyapatite crystals larger than typical of fresh bone but similar to those in specimens experimentally heated to around 645 °C. However, the specimens lacked other ultrastructural changes produced by this level of heat. Shipman et al. (1984) inferred that the Mesolithic sample's large apatite crystal structure was the product of diagenetic transformation (Chap. 16), and that X-ray diffraction could not distinguish culinary-level thermal stress on archaeofaunal specimens.

Taylor et al. (1995) explored whether geochemical signatures in bone could discern heat-stressed specimens, including those with no color shifts. Although thermal exposure caused changes in bone geochemistry, Taylor et al. (1995) found that these effects overlapped with those attributable to diagenetic effects alone. Nicholson (1992, 1993) conducted experiments parallel to those of Shipman et al. with bird, fish, and other vertebrate elements, which revealed development of similar features under thermal stress, with some intertaxonomic differences, as well as divergent durabilities of burnt specimens of different taxa.

Reseachers have explored whether other technological techniques for assessing bone microscopic structure could characterize structural changes – either in collagen or hydroxyapatite – associated with boiling, with some success. Koon et al. (2003, 2010) used Transmission Electron Microscopy (TEM) based approach to monitor changes in the organization of the collagen with boiling. They found that shifts in collagen structure took place at temperatures under 100 ° C, with fibrils assuming a "beaded," "dumbbell" form. Koon et al. (2003) note that similar changes can be seen in modern materials buried in a moor environment for 7 years. However, specimens from a single archaeological sample show divergences. Interpreted as reflecting boiling and lack of boiling within the sample (see also 2010). Bosch et al. (2011) analyzed sections of a modern human element boiled for 2, 4, and 5 h, using gas adsorption technique, X-ray diffraction and scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy, to explore the efficacy of each approach, using their results as a baseline for exploring textural changes in Neolithic bone samples. Only SEM imaging revealed a boiling-related change, in progressive smoothing of the basic bone surface structure at the more extreme durations of boiling. They attribute this to changes in collagen, which nonetheless is somewhat protected by the mineral matrix. Their examination of the Neolithic bone sample revealed that some specimens resembled those boiled for about 4 h, but not for so much as 6 h, while specimens that did not show these structural changes displayed non-homogeneous disrupted surfaces, which they attribute to the action of algae and fungi (Chap. 16). Other divergences between archaeological specimens putatively boiled and unboiled specimens were noted in gas adsorption profiles, but, lacking experimental analogues, their sources are unclear. On one hand, these findings are less than encouraging to the many zooarchaeologists who lack the equipment or funds to use TEM or SEM to discern such microscopic alterations on substantial samples of specimens. On the other hand, TEM and SEM are relatively common and accessible technologies, should one wish to explore whether boiling was a means of processing vertebrates in a sample. With regard to boiling and heating, readers are also referred to the work of Karr and Outram reported in Chap. 11.

Stiner et al. (1995) experimentally assessed the effects of bone specimens placed directly into fires and buried in sediments below fires. They monitored visible color shifts and shifts in bioapatite crystallinity, using FTIR spectroscopy, as well as exploring the fragility of burned specimens, compared to fresh bone specimens. Properties of heat-stressed and unburned specimens were also compared to those of experimentally monitored weathered elements (Chap. 15) and diagenetically altered archaeological specimens. They established that experimental specimens buried up to 5 cm below fires were partly or entirely blackened but that color shifts proceeded no further toward calcination. This is a significant finding because traces of thermal alteration into the carbonized range are common in many archaeofaunas, whereas actualistic research indicates that black, gray, or white bone colors are seldom produced during cooking itself.

Stiner et al. (1995) reported that Hayonim Cave archaeofaunal specimens categorized as burned by their color were depleted of organic material, whereas specimens lacking such color shifts retained fair amounts of collagen or its by-products, even millennia after burial. They also reported that carbonized (burned black) experimental specimens broke into smaller fragments when trampled in sediments or agitated in a box than did unburned or less heat-stressed specimens. The near-complete consumption of collagen in carbonized bones would reduce their resilience. As the Shipman and Taylor research teams, Stiner et al. encountered equifinality between products of heating, weathering, and diagenesis. Burned bone showed higher crystallinity, reflecting rapid bioapatite shifts into larger crystals under heat stress. However, similar recrystallization effects were produced by 1–2 years' exposure of *unburned* bones to weathering in hot, arid environments, as well as being seen unburned archaeofaunal specimens from Hayonim.

Bennett (1999) extended experimental research on effects of fires burning above buried bones, burying bones at varying depths in both clay and sand matrices with thermal sensing units. Fires above each unit were maintained for 48 h, with hourly temperature monitoring during 40 h of the firing, five checks during the 12 h immediately after the firing ended. While both units followed roughly similar heating and cool-down curves, the clay unit heated to a higher temperature than the sand unit. Temperatures did not exceed 500 °C (932 °C) in the substrate. Bones as deep as 10 cm below the surface turned black. Bennett (1999:7) notes that those at shallower depths were in the process of calcination, and that this kind of alteration may be confused with diagenetic alteration.

15.6.3 Thermal Alteration: Bone Surface Changes

Buikstra and Swegle (1989) experimentally cremated human bone to elucidate how deposits of cremated bones in some U.S. Midwestern archaeological sites were created, and their findings are relevant to zooarchaeologists. Heating human cadavers and bone with and without flesh in open fires and in a high-temperature oven, Buikstra and Swegle found differences in the extent of bone color shifts, surface cracking, and flaking, depending upon whether the bone was covered with flesh. Some bones that never developed color shifts through the experiment nonetheless developed hairline cracking and flaking on their outer surfaces as a result of thermal stress.

White (1992) noted similar patterns of bone surface modification on archaeological human bones, and I noted hairline cracks and shallow exfoliation on some parts of ethnoarchaeological ungulate long bone specimens that displayed brown color shifts on other portions (Gifford-Gonzalez 1989). If one were unfamiliar with bone weathering, these changes might be mistaken for Behrensmeyer Weathering Stages One or Two (Chap. 16). Careful comparison revealed that thermal cracking was developed without alignment with an element's osteonal structure.

15.6.4 Thermal Alteration: Bone Fracture Patterns

Chapter 11 noted that fracture patterns on previously heated bone differ from those on fresh bone. Oliver's (1993) ethnoarchaeological study among the Hadza of Tanzania documented transverse fractures of large ungulate long bones after marrow cooking. As illustrated in Chap. 11, I noted relatively high frequencies of transverse breaks with stepped break surfaces on ethnoarchaeological long bones with evidence for heating and a sample time frame that excluded the possibility of weathering (Gifford-Gonzalez 1989). Outram (2002) undertook experiments assess the prediction that long bones exposed to thermal stress would transmit force and fracture differently than do fresh bones. His results indicated that the highest sustained temperatures affected how experimental bones broke. Outram illustrates two cattle radii, one boiled (≥100 °C, 212 °F) for 10 min and then fractured, and one heated in an oven at 100 °C (212 °F) for 5 h before breakage. The first radius fractured in helical fashion, but more transversely than would be expected with fresh bone, and fresh bone break surface features were absent. The baked bone broke transversely, with rough and jagged break surface, much like those reported for heated ethnoarchaeological specimens by Oliver (1993) and myself (Gifford-Gonzalez 1989). Other studies indicate similar effects of heating on mammal long-bone breakage. Bonnichsen (1973) noted that Calling Lake Cree informants heated defleshed long bones to prepare them for breakage, and that informants said heating made breakage easier.

Shortening of collagen fibers is probably responsible for the divergences in fracture properties of fresh versus heated bone. Richter's (1986) experimental observations showed collagen strands in fish bone began to unravel and denature when baked at temperatures between 60 °C (140 °F) and 100 °C (212 °F) for 30 min. Collagen in fish bones boiled (≥100 °C, 212 °F) for 30 min was completely denatured. She suggested that collagen in mammal bone may be somewhat more protected from heating effects than it is in thinner fish elements.

However, some cautions should be noted. Although it is true that heating may alter bone's ability to resist stress, it is not true that jagged, transverse breaks can only be produced after thermal stress. Taylor et al. (1995) demonstrated that diagenetic transformations of bone collagen replicate those of thermal stress. Thus, neither break shape nor collagen alteration cannot definitively reflect exposure to fire, and all possible lines of evidence should be used for such inferences. Boiling and pit roasting in earth ovens may leave no color shifts or flaking and cracking from thermal stress on bones. Analysts working in situations where contextual evidence indicates that these culinary techniques may have been employed should consider whether bone breakage patterns within a given taxon reflect different stages or types of culinary techniques.

15.6.5 Bone as Fuel

The use of fatty bone as fuel has been an item of zooarchaeological folklore for some time, but it only recently came under systematic study. Costamagno, Théry-Parisot, and coworkers (Costamagno et al. 2005; Théry-Parisot 2002) undertook experiments to elucidate the extreme burning in archaeofaunas from the French Upper Palaeolithic Aurignacian industry. Among the most interesting findings of their detailed experimentation is that fatty bone produces high flames for up to an hour after initial combustion but does not maintain heat from embers after those flames have died down, as does wood (Costamagno et al. 2005). The authors suggest that fat-rich bones are useful in combination with wood for a longer burn, as well as for drying via convection heating in wood-poor environments. Costamagno et al. (2005) list taphonomic evidence of fuel use of bones, including evidence for entire long bones, as these burn longer than fragments, and calcination of cancellous tissues. Use of bone as fuel or fire starters may have continued in later times, as suggested by accumulations of sheep horn cores in the metalworking sector of the medieval Moroccan city of al-Basra (Benco et al. 2002). Horn cores produce dense, waxy secretions that in life maintain the integrity of the horn sheath; these readily ignite and burn.

15.6.6 Evidence of Pot Boiling: Pot Sizing

In the absence of a clear signal of boiling from bone color, chemistry, or ultrastructure, the modal size of bone fragments may indirectly reflect this form of cooking. Bones boiled in stone, ceramic, or metal vessels may be chopped or percussion fractured to fit into pots, as Yellen (1991) reported for large animal elements chopped to fit into pots by !Kung foragers.

Exploring the higher fragmentation rates among domestic cattle, as opposed to sheep and goat specimens from the Neolithic archaeofauna at Ngamuriak, Kenya, Marshall (1990) noted that fragments' maximum dimensions were smaller than or overlapping with rim diameters of ceramic vessels from the site. Marshall therefore interpreted the taxon-specific fragmentation as pot sizing. I observed sagittal and transverse chopping of cattle and zebra vertebrae with bush-knives into roughly equal-sized sections in an ethnoarchaeological pastoralist sample, probably reflecting pot sizing to aluminum cook pots used for cooking meat (Fig. 15.4b). Analysts who suspect archaeofaunal specimens might have been boiled in vessels may wish to assess pot sizing by checking the bone specimens' modal maximum dimensions against modal pot mouth dimensions.

15.6.7 Evidence of Pot Boiling: Pot Polish

Some ceramic pots have coarse inner surfaces, replicating an abrasive sedimentary matrix, and stirring bone fragments in such vessels can develop abrasion on bone tissue. The most detailed treatment of pot polish is White's (1992) analysis of traces of Late Ancestral Pueblo cannibalism in the Mancos region. He noted polishing and beveling on human and deer diaphyseal fragments from several sites. To clarify modification processes, White experimentally fractured deer metapodia and boiled them in a Pueblo plainware ceramic pot for 3 h to mimic stewing. Of 69 specimens processed, 41 showed either rounding by abrasion on broken and projecting diaphyseal ends or rounding with beveling on similar breaks. No rounding was noted on

Fig. 15.5 Pot-polish on diaphyses: center: purported pot-polish on a human femoral fragment from a Mancos Canyon pueblo, 5MTUMR-2346, Colorado, flanked by SEM micrographs of experimentally produced analogue in deer metapodial fragments. White bar = 1 cm. (From White (1992:128, Fig. 6.8), used with permission of T. D. White and Princeton University Press)

epiphyseal surfaces. White infers that beveling is the result of directional stirring during cooking. White's illustrations (Fig. 15.5) of experimentally modified diaphyses and prehistoric human and deer bone show striae running longitudinally from the polished, rounded, and beveled edges. If an archaeofauna derives from a site with stone or ceramic cooking vessels, zooarchaeologists may wish to inspect diaphysis break surfaces for polish and beveling as an aid in defining culinary processing included boiling.

15.6.8 Bone Grease Extraction

The signature of bone grease extraction comprises dense concentrations of small, minimally identifiable bone scraps, commonly 1–5 cm in maximum dimension (Outram 2001). Leechman (1951), Bonnichsen and Will (1980), and Binford (1978) reported on grease rendering from bone fragments, and Outram (2001) offered further details on the process and its by-products. Brink (1997) and Church and Lyman (2003) present comprehensive bibliographic overviews.

Based on experiments with deer long bones broken into different sizes, Church and Lyman (2003) concluded that efficient grease extraction does not require the degree of fragmentation typical of ethnographic assemblages. Because no statistically significant difference in the amounts of bone grease rendered from fragments from 4 down to 1 cm in dimension, they speculated that nutrients other than lipids may have been the main motivator for expending they energy to break bones into very small fragments. Janzen et al. (2014) explored an alternate explanation for this extreme fragmentation, implicating the thermal inertia of water and fuel economy.[1] In a series trials with cattle femora of the same sizes as in the Church and Lyman experiment, Janzen et al. (2014) measured grease extraction and fuel consumption in relation to water volume. Their results supported Church and Lyman's finding that grease yield does not significantly increase in fragments <4 cm. Their trials demonstrated that smaller fragment sizes required less water, and hence fuel, to achieve a grease-extracting simmer. Janzen et al. (2014) suggested that ethnographic cases might represent a tradeoff between the effort required to produce very small fragments and broader energy budgets than those involved in grease rendering. For example, if fuel were scarce or energetically expensive to obtain, bone fragmentation tactics might lead to broader efficiencies in overall household activities.

15.7 Can Household Culinary Refuse Be Discerned Archaeologically?

Can culinary and preservational activities be discerned in archaeofaunal samples? Under certain circumstances, culinary refuse deposits can be distinguished. This section begins with an example from my ethnoarchaeological research, then cites three archaeological cases where secondary culinary refuse was discerned. It then sketches a method for identifying such deposits.

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[1] While an undergraduate in my department, archaeologist Benjamin Broyles made a small-scale study that produced similar grease yield results to those of Church and Lyman. He proposed that extreme bone fragmentation could be intended to optimize fuel efficiency, as the thermal inertia of water requires considerable fuel to heat water to a simmer (Broyles, personal communication 1998). The Janzen et al. experiments explored this hypothesis.

Fig. 15.6 Aerial view of an abandoned Dassanetch defensive settlement (foreground) and an occupied one (background) showing overlapping animal pens around a central area for portable houses, near Ileret, Marsabit District, Kenya (Photograph by the author, over-flight courtesy Richard E. F. Leakey, 1974)

15.7.1 An Ethnoarchaeological Case

In the 1970s and the 1980s, the Dassanetch people of northeastern Lake Turkana were self-supporting for food, having access neither to markets nor to humanitarian food aid because of Kenyan and Sudanese government policies. The land away from the lake was semiarid bush and steppe (Carr 1977), with variable rainfall averaging less than 400 mm annually. Although viewing themselves as pastoralists, they grew sorghum and legumes via flood recession cultivation. Livestock sustained households during dry years, and poorer Dassanetch took fish and lake reptiles. The Dassanetch then had hostile relations with two other regional ethnic groups. Raiders took cattle and also killed as many people as possible, including women and children. Dassanetch residential settlements had a defensive layout, with portable houses inside a ring of livestock pens fenced with thorn tree boughs (Fig. 15.6).

Only livestock giving milk could be sustained on the sparse forage around the settlements. Other cattle and small stock were sent to stock camps tended by armed youths and younger boys. If environs of residential settlements became grazed out, families' milking stock could lose condition and fail as a crucial food source. Moving stock and homes to better grazing had to be balanced against risks of losing animals and family members in raids. One tactic was for 10–20 households with sufficient armed men to repel raiders to set up a large-scale temporary camps in better grazing areas. These resembled defensive residential settlements in their size and layout but were occupied a shorter time. Site 105 was such an encampment, occupied for 6 weeks in July–August 1973 by about 34 Dassanetch pastoralist households. I mapped the site in October 1973, collecting bones from animal pens, house interiors, and the "house area," the spaces between the houses.

Beginning with what I knew of Dassanetch butchery practices, space use, and refuse disposal, I explored whether specimens from these sectors reflected different steps in the chain of processing and discard. I selected parameters of faunal samples

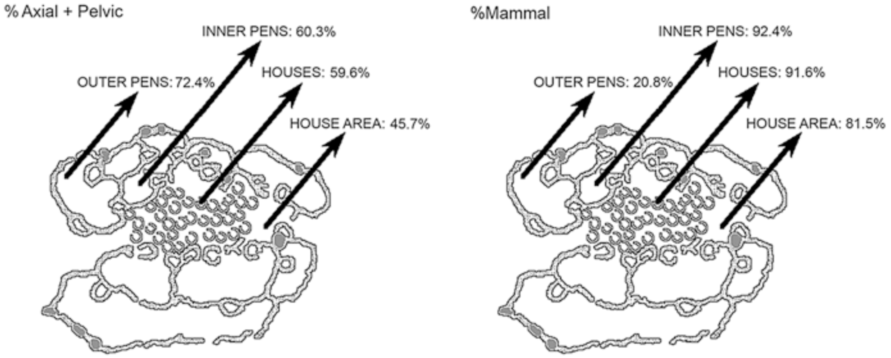

Fig. 15.7 Site 105: results of spatial content analysis for body segments and for taxonomic composition for *left*: frequencies, as %NISP, of axial+pelvic specimens in four zones of the site. Frequencies of the sample from inside all houses and that from the inner pens are virtually identical, while those of other zones diverge; *right* %NISP of mammalian specimens (vs. reptile and fish) in the same sampling zones. Frequencies are also virtually identical from the two respective sample areas, while those of other zones diverge. (Figure by author)

that could be transferred to archaeofaunal cases lacking such contextual information. Dassanetch butchers separated caprine appendicular segments from the axial skeleton distinctively: the scapula was removed with the foreleg, while pelvic bones remained articulated to the axial skeleton, the hindleg being detached at the femoral head. Separated units of a single animal could be cooked in disparate ways (Fig. 15.4a–c). Dassanetch women cleaned hearths in their houses by gathering up ash and food debris and throwing these into or over the fences of the innermost, sheep and goat pens surrounding the house area. I reasoned that secondary refuse from culinary processing would resemble the samples recovered from within the houses, which held abandonment debris of inhabitants' last few meals.

I compared proportions of appendicular (including scapula) elements to axial (including pelvis) elements across four aggregated samples: houses, house area, inner pens, and outer pens, also comparing proportions of mammals to non-mammals in the same subsamples. I hypothesized that the proportions of body segments and taxa within the houses should be similar to deposits in the inner pens, the end-points of processing I had observed in occupied localities. I expected that proportions of mammal to non-mammal specimens might vary among households, according on their owners' wealth, but that aggregate pattern of all houses would be paralleled by the aggregate of secondary refuse.

Actual proportions of axial to appendicular elements in the houses (locale of culinary processing) and the innermost pens (locale of culinary refuse disposal) were disconcertingly convergent (Fig. 15.7). Proportions in these two zones contrasted with those in the house area. Taxonomic proportions of the assemblages from the houses and pens were also extremely similar (Fig. 15.7) and contrasted with proportions of taxa from the house area sample. I infer that the house area aggregate reflects from different point in the processing and discard chain than the samples from inside the houses and from the inner pens. These also differed from the sample the outer pens, probably reflecting yet another processing stage. Thus, a simple comparison of intrasite subsamples, using uniform properties of animal bodies and taxonomic abundances, with knowledge of the location of culinary facilities, established with strong probability the locations of household secondary refuse.

15.7.2 Does It Work Archaeologically?

Is this just an ethnoarchaeological parlor trick or a potentially productive method for studying culinary and preservational processing archaeologically? Grantham (1995) explored variations in culinary processing and osteological outcomes among Druze people in the Golan Heights on the border of Israel and Lebanon and analyzed archaeofauna from Tel Hazor, a Late Bronze–Early Iron Age site in ancient Canaan. Druze handling of sheep for feasting produced an osteological residue distinct in its composition and locations from that of everyday meal debris that included sheep. Grantham (1995) reported that similarly differentiated types of bone debris were perceptible in spatially distinct Tel Hazor archaeofaunal sub-samples. In the Andean Moche Valley, Pozorski (1979) found similar correspondences between faunal debris associated with loci of culinary processing and the secondary refuse deposit outside the house compound studied. Russell and Martin (2005) distinguished household culinary debris from that of communal feasts in the Çatalhöyük archaeofauna, again using sub-sample composition and spatial contextual data.

These archaeological cases suggest that such an approach can be productive in relatively large-scale sites representing considerable depositional time, so long as some intrasite spatial structure is documented. If animal processing and disposal were constrained by permanent architecture – and, one imagines, by cultural practices – this could produce redundancies in the composition of deposits that endure over time. Such an analysis requires definition of cooking features and primary refuse in these zones of food preparation. Microdebris analysis (e.g. Stahl and Zeidler 1990; Bogaard et al. 2009) is particularly useful for this, as it can reflect not only the locales but also the types of culinary processing. Secondary refuse deposits may be discerned empirically through comparative sampling and compositional analyses in areas away from such functional zones or in features containing animal remains. Other lines of evidence, such as ash and broken culinary artifacts, might help define such deposits. I believe that such analyses are facilitated by a *chaîne opératoire* approach that identifies sequential stages of processing and discard and offers a functional framework for analyzing bone modifications (Fig. 15.1). This kind of analysis is not the first thing one does with an archaeofauna, but rather something one can explore once one has a grasp of "forensic reconstructions" of taxon-specific handling. Of course, such explorations are only workable with sites occupied long enough for refuse from meals to have been secondarily deposited.

Precedents for intrasite compositional analysis exist in zooarchaeological analyses of food sharing. Enloe and David (1992; Enloe et al. 1994) studied carcass subdivision in the Magdalenian sites of Pincevint and Verberie, France, as did Pozorski (1979) with Andean Moche archaeofaunal samples (Chap. 25). They did so by comparative analysis of the osteological *composition* of spatially discrete bone clusters, combined with refitting of individual reindeer carcasses. Enloe and David addressed subdivision of reindeer carcasses among households and did not explicitly address culinary processing, while Pozorski did, but compositional analysis appears to be a good strategy for analyzing culinary practices. Such approaches ultimately depend on a knowledge of the sequence of carcass dismemberment, also pioneered by Frison et al. (1976). Although they put the data produced from compositional analysis to a very different use, Muir and Driver (2002) defined spatially distinct deposits within Pueblo III phase sites, including household refuse, and analyzed their composition to explore differences in animal use, sites of varied sizes and architectural features in the northern San Juan region.

If we take a product-focused approach to zooarchaeological materials, we must include culinary processing. Human meals are products of tool-mediated, preconsumption manipulation where the benefits of the food quest are realized. Its output comprises most of what we recover from archaeological sites, whether debris of a marrow snack at a butchery locale or heaps of household trash in a city. The nutritional and time benefits conferred by culinary processing incur added energetic costs in producing facilities and implements and fuel acquisition. Work allocation and mobility strategies must accommodate these activities. Zooarchaeologists cannot fully contribute their skills to addressing the feedbacks of food processing technology, anatomical form, and social relations over human evolutionary time, nor the roles animal foods played in emergent social relations and cultural systems, until we better grasp the distinctive aspects of materials that have undergone culinary processing.

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Chapter 16
Invertebrate, Plant, and Geological Effects on Bone

This chapter describes the effects of invertebrates, plants, and geological processes that manifest as bone surface modifications or as altered element frequencies in archaeofaunal samples. Familiarity with bone surface modifying effects of plant roots, fungi, bacteria, and insects helps zooarchaeologists to avoid confusing these modifications with those of other actors discussed in this section. Sediments carried by wind and water can abrade bone surfaces, acting as another source of this bone surface modification. Bone weathering on land surfaces gradually and selectively reduces skeletal elements' integrity, at the same time imparting information about pre-depositional processes that affected an assemblage. Flowing water can selectively winnow a vertebrate assemblage by transporting some skeletal elements and not others, according to their hydrodynamic properties. Research has established that bone mineralization may begin before an element is buried. Appreciating the signatures of geological effects in archaeofaunas facilitates more informed analyses. The next sections discuss biological agents, and the final sections treat effects of geological processes.

16.1 Invertebrate Effects

This section provides a brief overview of bone modification by insects and microbial actors. Invertebrates modify bone at both macroscopic and microscopic levels, altering it externally and internally.

D. Gifford-Gonzalez, *An Introduction to Zooarchaeology*,
https://doi.org/10.1007/978-3-319-65682-3_16

16.1.1 Mechanical and Chemical Effects of Insects

Paleontologists have actualistically investigated insect effects on bone to shed light on fossil bone surface modifications. Bader et al. (2009) provide an excellent overview of invertebrate taxa that use bones for food, shelter, or for egg deposit and pupation. Zooarchaeologists can also refer to studies of invertebrate consumer impacts on bones, including the forensic literature on insect succession in human cadavers (see citations in Bader et al. 2009).

Teneid moths consume skin, feathers, hair, and horn sheaths and lay their eggs close to a keratinous tissue source for their hatching larvae to consume. When feeding, larvae etch long grooves in horn cores or bone (Bader et al. 2009). Behrensmeyer (1978; see also Behrensmeyer et al. 1989) illustrates channels in horn cores by *Tinea deperdella* that might be mistaken for carnivore tooth scores. Some tropical termites inflict mechanical damage on bone by building their nest walls against the underside of a bone resting on a land surface, then chewing away layers of bone within the nest (Bader et al. 2009). Termite gnawing expands as lines from a central point, at times producing star-shaped excavations of the bone surface. This behavior appears to be motivated by the termites' need for nitrogen in some tropical environments (Fejfar and Kaiser 2005). Figure 16.1 shows examples on fossil bones collected at Laeotoli, Tanzania.

Bader et al. (2009) use analogy with contemporary dermestid beetle pupation chambers in wood or cardboard to attribute the shallow "rosettes" and circular pits common in dinosaur bones in the Upper Jurassic Morrison Formation of Wyoming. They propose that, in the absence of wood, Jurassic dermestid larvae may have made their pupation chambers by chewing pits into dried flesh down to the bone, in an inward-spiraling action. If the chewing process were to be interrupted before it is completed, a "rosette" with a central pedestal remains (Fig. 16.2), but full chamber construction would remove the central area and leave a shallow circular trace. The larva would seal the chamber from the inside with material from its final molt and begin pupation.

16.1.2 Microbial Bioerosion: Surface and Deep Tissue Modifications

Jans (2008) offers a comprehensive review of the present state of knowledge about microbial effects, often called *bioerosion*, on bone surfaces and histological structure. The bioerosion most likely to be seen by archaeologists are channels on the periosteal surfaces of bones rather than tunnels inside bone tissue. Such channels have been implicated in one zooarchaeological controversy – between Domínguez-Rodrigo and Barba (2006, 2007) on the one side and Blumenschine et al. (2007) on the other – over whether all marks identified as carnivore-tooth scores by one set of researchers are actually tooth marks or whether some are bioerosion channels.

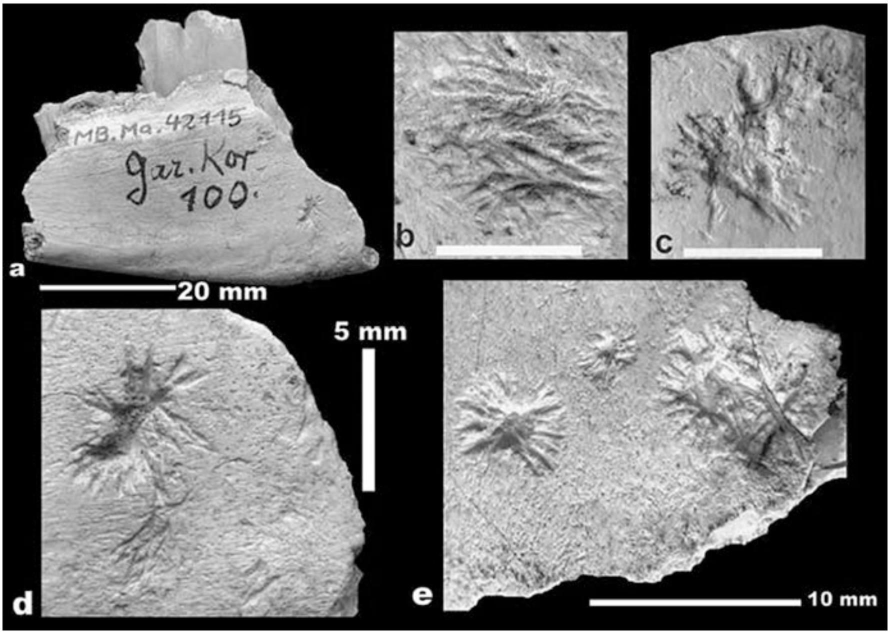
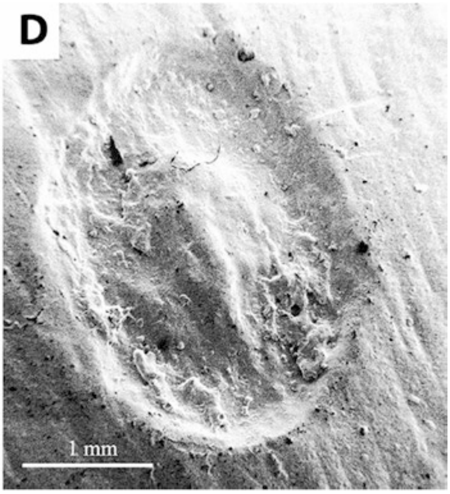


Fig. 16.1 Marks made by termites on ungulate bones, on the mandible of a small bovid from Pliocene beds in southern Serengeti, Tanzania. Specimen collected by the 1934–1936 Kohl-Larsen Expedition and presently housed in the Museum of Natural History, Berlin. (**a**-**e**) show traces on the lingual and buccal sides of the lower jaw (MB. Ba. 42,115, Gar.Kor.100). Scale for (**b**-**c**) is 5 mm. (Photograph by O. Fejfar 2004, used with his permission, published in *Paleontologica Electronica*, an Open Access journal)

Fig. 16.2 Circular traces in dinosaur bone surfaces, showing pedestal and scalloped edges, from the Morrison Formation modification to dinosaur bone (Bader et al. 2009:Fig. 7D), which Bader et al. (2009) attribute to dermestid activity. (Used with permission of the authors and the Society for Sedimentary Geology)



The debate provides excellent references on and illustrations of these marks, as well as outlining potentially ambiguous areas of morphological overlap with tooth marks. Microbial effects on the internal structure of bone is less immediately visible but have been shown to affect the survival of archaeofaunal specimens as well as being implicated in diagenesis. The latter will be discussed in a later section of this chapter (16.6 Diagenesis: Not Just for the Deeply Buried).

Wedl (1864), a paleontologist, first described surface channeling and tunnels in bones, teeth, corals, and other hard tissues, and these were later named after him. Experiments have established that fungi are the causal agents of Wedl tunnels. Experiments have established that fungi cause Wedl tunnels. Jans et al. (2004) note that, under SEM imaging, Wedl tunnels appear empty, with well-defined walls, implying that both collagen and bone mineral are mobilized and transported away from the tunnel by the fungi. Wedl tunnels transgress bone tissue's osteonal structures and do not proliferate along them (Jans 2008). Based on their size and points of origin, Trueman and Martill (2002) divided Wedl tunnels into two types:

1. Type 1 Wedl tunnels, the most common form, arise at the natural surface of a bone or other calcified tissues, or from a break surface. They are randomly branched networks of tunnels 10–15 microns in diameter.
2. Type 2 Wedl tunnels are smaller (five microns diameter) and are more rare. Unlike Type 1 tunnels, these extend into the bone matrix from Haversian canals (Chap. 4) rather than from outer or break surfaces and display greater reticulation.

Hackett (1981) distinguished three additional types of bioerosion, or "microscopic(al) focal destructions" or MFD's. Unlike Type 1 Wedl tunnels, MFD follow blood circulation systems within the bone tissue, rather than developing from bone surfaces. They are distributed either longitudinally or at right angles to osteons but apparently do not extend through cement lines (Jans 2008). Hackett further broke MFD's down into lamellate, linear longitudinal, and budded variants (Fig. 16.3), and the last may transgress linear bone organization (Davis 1997). They may be aligned in different planes relative to the osteons and are 10–30 microns in diameter (Trueman and Martill 2002).

MFD alterations are attributed to bacterial action, with species of the genus *Colostridum* being the primary suspect, augmented by cyanobacteria (formerly "blue-green algae") activity in elements in water (Davis 1997). Experimental research on bacterial effects has not been as successful in delineating the precise mechanism of bone modification as has been research on fungal bioerosion (Jans 2008). However, Jans et al. (2004) cite evidence that bacterial attack on bone begins soon after death, following vascular paths of the body into bone. Jans (2008) argues that endogenous gut bacteria, which migrate from the gut into the rest of the body within a few hours after death, may be among the first colonists of bone. In bacterial MFD's, mineral deposition can be extensive, lining tunnels with dense mineralized tissues, with manganese a common precipitate (Fernández-Jalvo and Andrews 2016), whereas cyanobacteria do not deposit minerals into their tunnels (Fig. 16.4).

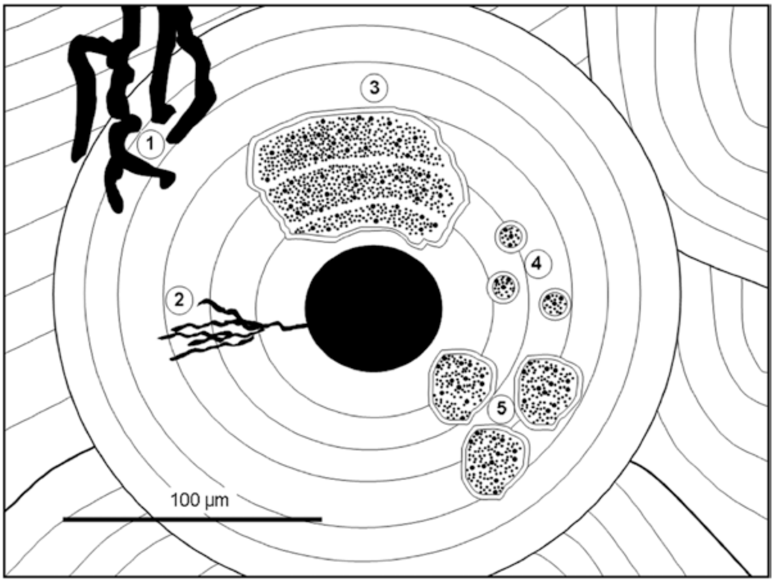
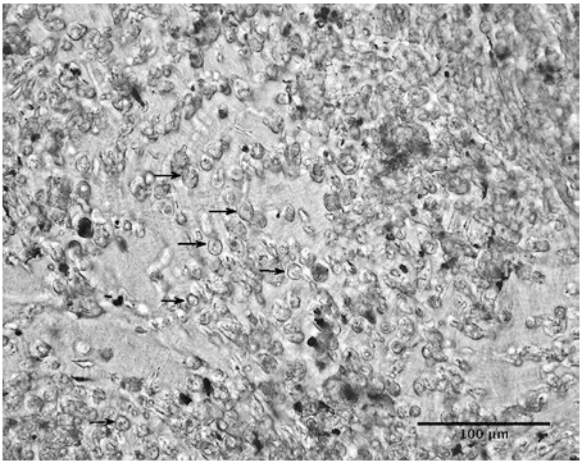


Fig. 16.3 Schematic representation of five types of tunneling as described by Hackett 1981: 1: Wedl Type 1 (fungal), 2: Wedl Type 2 (fungal), 3: lamellate MFD (bacterial), 4: linear-longitudinal MFD (bacterial), 5: budded MFD (bacterial). (From Jans 2008:Fig. 1, used with permission of author M. M. E. Jans and Springer)

Fig. 16.4 Transverse section of bone with many linear longitudinal tunnels (arrows), averaging c. 10 µm, with dense mineralized rims and infill. Osteonal structure of the bone is nearly obliterated. (From Jans 2008: Fig. 3, used with permission of M. M. E. Jans and Elsevier)



Davis's (1997) experiments on bird bone bioerosion by algae and cyanobacteria in freshwater and nearshore marine environments in south Florida, U.S.A. supported earlier findings from forensics, archaeology, and paleontology:

1. Tunneling occurs within a few days of exposure, and is often accompanied by green or blue-green staining (Davis 1997:394).

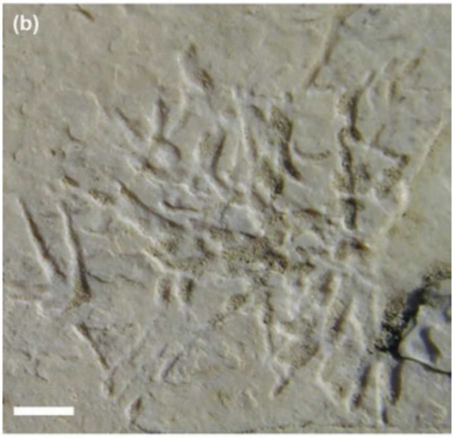


Fig. 16.5 Bioerosion channels (*center*) on fossil bovid long bone from Olduvai Gorge. Scale bar: 2 mm. (From Blumenschine et al. 2007:Fig. 1, used with permission of Elsevier)

2. The bioerosive organisms were endolithic (living within rocks and other hard matter) cyanobacteria and algae, which entered bones via natural pores as well as establishing periosteal colonies, where they etched meandering channels (Fig. 16.5).
3. Burial inhibits bacterial and algal colonization and bioerosion. Some partly buried bones displayed bioerosion on their exposed sections but none on their buried segments.
4. Fattier elements resisted bioerosion (Davis 1997:395).

Jans (2008) noted that articulated skeletons appeared to be less vulnerable to fungal Wedl tunnels but more so to bacterial attack. This is probably because of the postmortem maintenance of the circulatory system in interred bodies, which would facilitate swift and extensive bacterial infiltration of bone.

16.2 Dendritic Erosion (Root Etching)

Plant roots can grow on and around buried bones, and their root secrete weak acids that can dissolve bone’s hydroxyapatite, leaving irregular networks of shallow grooves. Fernández-Jalvo and Andrews (2016: Figs. 1.2, A125, A154) illustrate cutting marks overlain by root marks and a set of carnivore tooth scores, which clearly show the differences between cut marks, carnivore scores, and dendritic etching. Root marks normally meander more than do carnivore tooth scores, and, because they form by dissolving the bone, they display no “crushing-up” of bone tissue. Root etching lacks the striations and shouldering of cut marks or pseudo-cut marks. White and Folkens (2005:57) note that dendritic markings may appear lighter than the main bone surface, due to root acids’ more recent exposure of fresh bone. I have noticed that the top edges of some root marks appear to slightly overhang the groove beneath, possibly due to undercutting of bone by secreted acids of

Fig. 16.6 SEM micrograph showing the U-shaped section typical of root etching, or dendritic marking, produced on the bone surface of a recent cow element buried and monitored for 8 years, at Draycott, Somerset, UK. Scale: upper left bars: 400 microns. (From Fernández-Jalvo and Andrews (2016:Fig. A232), used with permission of authors and Springer)

roots already embedded in the fabric of the bone (Fig. 16.6). Andrews (1990:19-20) states that extreme dendritic etching can cover so much of an element in overlapping layers that it resembles surface corrosion by an extremely acidic or basic matrix. He argues that, even in such cases, it is possible to discern some shallow roots tracks on the bone surface.

16.3 Weathering

As a skeletal element loses the moisture content typical of its living state, hairline cracks may develop in the outer cortical bone. Elements lying exposed on land surfaces begin to crack and flake, gradually losing their outermost layers of cortical bone, exposing the osteonal structures underneath. Some cracks begin to penetrate into bone cavities, reducing the integrity of the element and rendering it vulnerable to mechanical damage (Fig. 16.7). This process is called subaerial weathering.

Behrensmeyer's (1978) approach to describing weathering followed earlier efforts (e.g. G. J. Miller 1975) and formed the focus of further weathering research. Her research began with a longitudinal actualistic study monitoring 35 mammal carcasses of known death dates, supplemented by observations of 1500 more carcasses with less definite but reasonably estimated elapsed times since death, in Amboseli National Park, Kenya. The project monitored weathering in six habitats in the Amboseli lake basin. As a paleontologist interested in fossil deposit formation, Behrensmeyer and her colleagues continued longitudinal monitoring of Amboseli land surface vertebrate assemblages for more than 40 years (Cutler et al. 1999; J. H. Miller et al. 2014; Tuross et al. 1989; Tuross et al. 1989; Western and Behrensmeyer 2009). Behrensmeyer described six qualitative "Weathering Stages" (0–5) through which bones pass, outlined in Table 16.1. Behrensmeyer stipulated methods for recording the stages:

Fig. 16.7 Weathering stages and mechanical damage in bovid bones. *Top*. a metatarsal of a topi (*Damaliscus lunatus*) showing Weathering Stage 2, with deep longitudinal cracking, death + 2 years; *Bottom*. a trampled metatarsal of a topi the shaft of which has collapsed into columnar fragments along deep cracks developed by weathering, death + 4 years. (Photos by the author)

Table 16.1 Behrensmeyer (1978:151) Weathering Stage criteria

0	Fresh bone, no weathering cracks, bone is greasy and soft tissue may still be attached.
1	Bone shows cracking, normally parallel to the fiber orientation of the bone. Articular surfaces may display mosaic cracking. Soft tissues may still be present.
2	Outermost layers of bone show flaking, usually beginning from cracks that continue to develop in the bone. In long bones, long, thin flakes are normal. Flaking continues, becoming extensive and gradually removing all outer bone. Tissue may still be present.
3	Bone surface displays patches of rough, evenly weathered compact bone, showing the underlying fibrous texture of the bone. Weathering does not penetrate more than 1.0–1.5 mm at this stage. Patches of this exposed bone gradually spread over most of the bone. Break surfaces may be rounded at this stage. Tissues are seldom present.
4	Bone surface is coarsely fibrous, with rough texture. Large and small splinters of bone may fall from the bone. Weathering penetrates into bone cavities. Cracks in bone are open, with rounded or splintered edges.
5	Bone is actually falling apart in place. Large splinters lie around the main bone, which splinters or breaks up when moved.

1. The most advanced stage covering an area of more than one cm^2 is noted.
2. Flat surfaces of jaws, scapulae, innominates and shafts of long bones should be used and damaged areas avoided.
3. If more than one observer is present, all must agree on the stage.

Behrensmeyer found that weathering rates are influenced by bone temperature fluctuations, ambient moisture, and soil pH, and that vegetation cover mitigates the temperature and moisture swings that produce weathering, proceeding most slowly in swamp or dense woodland environments. Based on her observations, Behrensmeyer concluded:

Fig. 16.8 Influence of microenvironment on weathering rates: *Top*. two photos show a hippopotamus radius on well-drained ground at Weathering Stage 3 in 1974 (**a**) and in 1976 (**b**); *Bottom*. tibia of the same hippopotamus in a shallow depression, at Weathering Stage 4 in 1974 (**c**) and Stage 5 in 1976 (**d**). (Photos by author)

1. Elements of a single skeleton weather at different rates. Bones with high surface-area-to-volume ratios, such as mandibles, scapulae, and innominates, weather most swiftly and those with inverse ratios, such as carpals and tarsals, weather most slowly.
2. The same element may weather at disparate rates in different settings, according to overall habitat and to microenvironment, both of which govern factors outlined above (Fig. 16.8). See also Todd's (1983) experiments and notes on bone weathering and microenvironments.
3. Weathering stages do not describe postmortem disintegration of mammal teeth.

4. Elements of different mammal taxa weather at different rates. Bones from species less than 5 kg should not be assessed using this scheme.
5. Due to constructional differences, elements from reptiles, birds, and fish do not conform to this descriptive system and require their own assessments of weathering (see Behrensmeyer et al. 2003 for birds).

Various researchers used the Behrensmeyer system to describe large mammal bone weathering rates in a variety of modern environments. Haynes (1988) documented weathering elephant and other skeletal elements in Zimbabwe bushveld. Tappen (1995) monitored bone weathering in the savanna of the Democratic Republic of Congo. Gifford-Gonzalez (1984) calibrated weathering rates in arid East Lake Turkana, Kenya. Borrero (1990) evaluated weathering on guanaco bones in moist temperate Tierra del Fuego. Cruz (2008) did a parallel assessment of mammal and sea bird remains in various Patagonian habitats. Fiorillo (1995) commented on the influence of temperature on rates of weathering in North America, and Lyman and Fox (1989) monitored deer bones in a temperate forest setting. Binford (personal communication, 1978) observed that weathering proceeds very slowly with elements in permafrost, which are frozen for a long span each year, with century-old specimens still greasy and lacking cortical exfoliation.

Behrensmeyer's goal for developing this system was to formulate criteria by which the duration and conditions of formation of fossil assemblages could be monitored. She argued that low weathering stage diversity could reflect a synchronous span of exposure and burial, whereas high weathering stage diversity might reflect a longer-term, attritional accumulation. Despite Behrensmeyer's cautions, some zooarchaeologists (Potts 1986; Gifford et al. 1980) used weathering stages to estimate the rates of site formation at prehistoric archaeological sites. I now believe that my use of weathering stage data was an error, both because it was the sole line of evidence used and because I misidentified many elements that had lost their periosteal lamellae as Weathering Stage 0 (see below).

Lyman and Fox (1989) analyzed zooarchaeological uses of weathering and made several important points:

1. "Weathering profiles," the numeric tables or histograms displaying frequencies of various weathering stages, and the basis for elapsed accumulation time estimates, mask the fact that varying combinations of the disparate factors outlined by Behrensmeyer could produce similar profiles.
2. Archaeological accumulations differ from the "passive" land surface accumulations Behrensmeyer et al. described, because they normally result from selective collection of faunal remains to a central place. Human selectivity further complicates weathering profile interpretation, because it can differentially select taxa and elements, producing samples that diverge from natural animal deaths on a land surface.
3. Specimen interdependence is a problem when analyzing weathering in an archaeofaunal sample, as elements from the same skeleton are likely to co-occur. They recommend selecting a few, consistently selected bilaterally symmetrical element to assess weathering, for example, a left humerus and a right scapula.

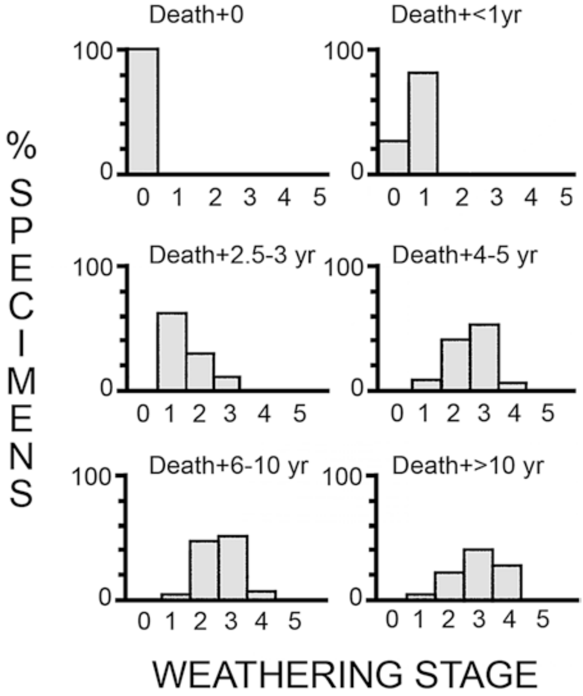


Fig. 16.9 Actualistic weathering stage succession data from Gifford-Gonzalez's (1984) longitudinal study of East Lake Turkana large ungulate taphonomic specimens. (Redrawn by author after Lyman and Fox 1989:301, Fig. 1, with permission of the authors and Elsevier)

4. Based on weathering-stage profiles documented in one longitudinal actualistic study of multiple ungulate elements (Gifford 1984; Fig. 16.9), they suggest that weathering stages of elements from carcasses that all began subaerial weathering over a short span of time fit a "wave model." At any given moment, skeletal elements' diversity of surface-area-to-volume ratios will produce an array of weathering stages, with the modal stages moving toward Stage 5 (or, practically, through Stage 4, as Stage 5 will be unquantifiable) over time (Fig. 16.10).

Lyman and Fox concluded that, given the multiple and variable factors affecting bone weathering, it is incautious to discuss the nature of pre-depositional accumulation based on weathering alone. They stressed that paleontological applications of weathering always employ multiple lines of evidence in addition to weathering when assessing the span and nature of bone accumulations.

Like Behrensmeyer et al., Argentine zooarchaeologists have taken a landscape-scale approach to actualistic investigations of taphonomy that includes weathering as one of many variables assessed. Borella and Muñoz (2006) demonstrated that marine mammal element frequencies and modal weathering stages vary according to the nature of the inputs (mass versus attritional mortality) and the depositional regimes of different coastal habitats in Tierra del Fuego. Belardi and Rindel (2008) found weathering patterns of different modern guanaco mass-mortality samples to be correlated with the geomorphic contexts. Cruz (2008) showed that weathering in contemporary land surface assemblages in Patagonia differed from region to region.

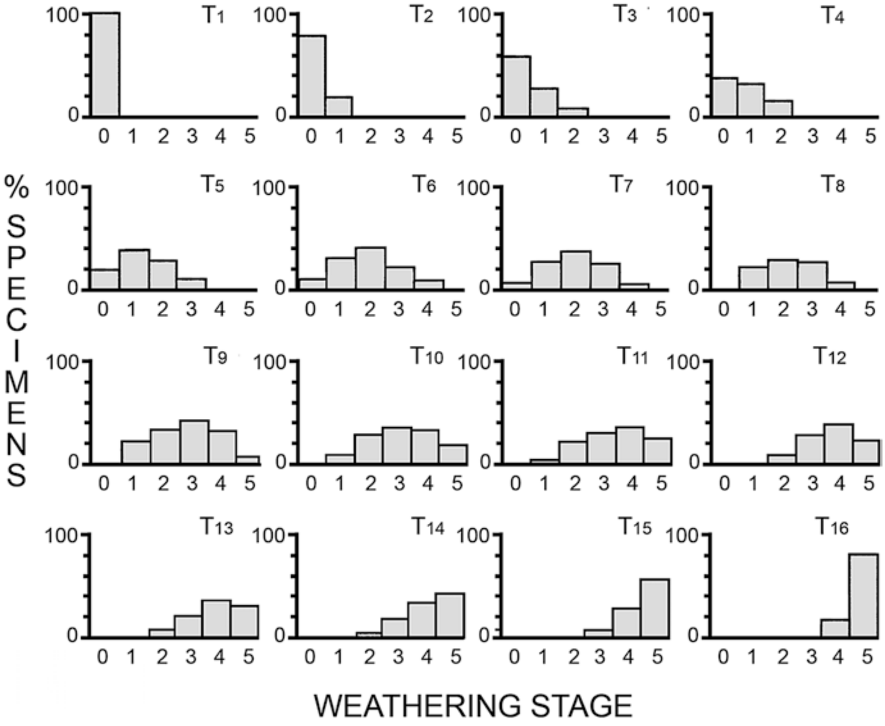


Fig. 16.10 Lyman and Fox's (1989) theoretical "wave model" of weathering stage succession. As the authors stress, Stage 5 specimens would not actually be "present" for observation as integral elements. (Redrawn by author after Lyman and Fox 1989:302 Fig. 2 with permission of the authors and Elsevier)

One practical aspect of zooarchaeological weathering analysis is making sure whether the bone surface examined is actually the original, periosteal surface. Archaeofaunal specimens may have complex taphonomic histories: heating without color changes may crack or flake periosteal lamellae, as can subaerial exposure to weathering. The depositional matrix can further modify weakened bone surfaces. Acidic soil can dissolve the outermost layers of lamellar bone exfolating in the initial stages of subaerial weathering. The early pastoralist archaeofauna from Prolonged Drift, Kenya (Gifford et al. 1980) was buried in clayey fluvial silts, and excavation photos show that, as specimens were lifted from the matrix, tiny bone flakes remained stuck to the clay matrix, in a kind of "facial peel" of Weathering Stage 2 flakes from bone surfaces. I initially interpreted some such bone surfaces as being at Stage 0, but re-inspection a decade later showed many specimens had "islands" of lamellar bone representing the original bone surface occasionally projecting above the surfaces that I had assumed were periosteal bone. Thin-sectioning specimens would have revealed disrupted periosteal lamellae, but few zooarchaeologists have the luxury of doing this with hundreds, if not thousands, of archaeofaunal specimens. Given this experience, I modified Behrensmeyer's weathering stages for the open sites with which I am presently working, adding a "<Stage 3" category. Despite potential confounding effects of sedimentary matrix and excavation methods on specimens in the Stage 0–2 continuum, one can definitively state whether or not a specimen has reached Weathering Stage 3. Including the <Stage 3 provides useful comparative information on the diversity of subaerial weathering in different archaeofaunal samples.

To sum up the present state of knowledge about bone weathering, larger mammals' skeletal elements on land surfaces consistently pass through predictable stages of disintegration, as collagen fibrils denature and cracks develop in ever-deeper and broader portions of the bone, regardless of climate zone. Different elements of a single animal can display a range of weathering stages. Weathering rates vary according to local conditions, with climate being an overriding influence. Weathering rates are slowest in equable humidity and temperature, as in deep shade, inside a cave, or even permafrost. Microenvironments affect weathering rates as local variations in pH, wetting and drying cycles, and heating advance collagen disintegration rates. These considerations indicate that archaeologists should be circumspect when applying weathering stage analysis to archaeological or paleontological assemblages, using this as one of several lines of evidence to reconstruct circumstances of site formation.

16.4 Abrasion

Abrasion is among the most problematic of all surface modifications to bone in terms of identifying the actor that created it. Mechanical smoothing, rounding, polishing, and attrition of surface features, at times accompanied by scratches and striations, can develop on bone in a variety of contexts, with very similar effectors and causal processes. Sedimentary particles propelled by wind, water, animals, and humans alter bone surfaces when in contact with them. Like cuts and trample marks, abrasion would seem to present a case of equifinality with the same causal processes and effectors producing similar outcomes regardless of the actor involved. However, Rogers (2000) noted that cases of "equifinality" sometimes result from underspecification of differing processes' outcomes. Some pioneering investigators of ancient hominins in Africa and of "early man" in the Americas argued that polished and abraded breaks on long-bone shafts could only have been created by human tool use, and subsequent actualistic research has clarified causes and subtle differences in outcomes of abrasion, the latter elucidated by application of SEM technology (Brain 1965, 1974; Thorson and Guthrie 1984; Shipman 1989; Olsen and Shipman 1988; Olsen 1989). Comparative study of hominin craniofacial growth must control for modification to osteological landmarks by postmortem abrasion (Bromage 1984) and has motivated careful study of abrasion effects.

16.4.1 Particle Impact vs. Sliding Abrasive Processes

Sedimentary particles impinging on a bone surface can produce different modifications, depending on the manner in which they come into contact with the element. Bromage (1984) experimentally monitored a number of causal processes, including flowing water without sediment, air-driven and water-driven particles, sliding abrasion by fine and coarse emery paper, brushing, and hand rubbing, using SEM to comparative assess bone surface modifications. Bromage's observations on particle impact and sliding abrasion are probably the most relevant to zooarchaeology.

Abrasion by *particle impact* and the *sliding abrasion* that develops as particles drag across a bone surface are often distinguishable. Particle impact abrasion, whether air- or water-driven, initially developed impact craters on the bone surface, with corresponding deletion of some bone mineral, that are apparent when examined at high magnification (Bromage 1984:Fig. 2). Severe particle impact (Bromage 1984:Fig. 4) completely removed surface lamellae and exposed the underlying osteonal organization. Water-borne sedimentary particles produced impact marks similar to those of airborne particles, but at lower intensities for the same duration of exposure and distance from propulsive source. Water without sedimentary particles flowing over bone at relatively high pressures (80 psi from 30 cm distance for 5 min) removed most bone surface lamellae. Shorter intervals resulted in less bone surface removal, but developed rounding of lacunae edges and other surface features (Fig. 16.11).

Sliding abrasion by particles moving in continuous contact with the bone surface produced grooves in the bone. Finer-grained particles left shallower grooves and removed a minimal amount of bone on initial contact (Fig. 16.12). Coarser-grained particles left broader, deeper grooves. Bromage noted that cleaning by brushing could create similar grooves in unmineralized bone by dragging particles of grit across the surface. Bromage (1984:166) also stated that hand rubbing reduced or eliminated bone structure details within minutes.

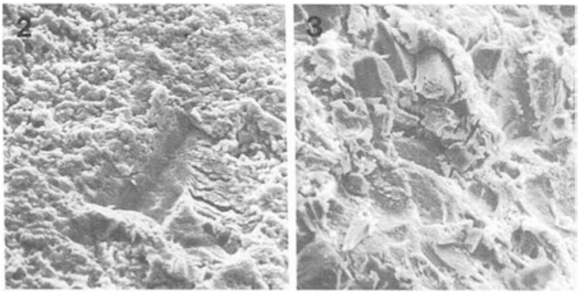


Fig. 16.11 SEM images of particle impact abrasion. **2.** Particle path gouged in bone; field width, 60 *μ*. **3.** Severe particle abrasion; field width 60 μ. (From Bromage 1984:165, used with permission of T. Bromage and Elsevier)

16.4.2 Tool Use Vs. Sedimentary Impacts

Given that most intentional human bone-toolmaking involves sliding abrasion, Bromage's findings have relevance to zooarchaeological analyses. Humans use sliding abrasion to form bone tools using abrasives such as sandstone or sand particles in a slurry with water (Fig. 16.13). Among the most interesting facts to emerge from

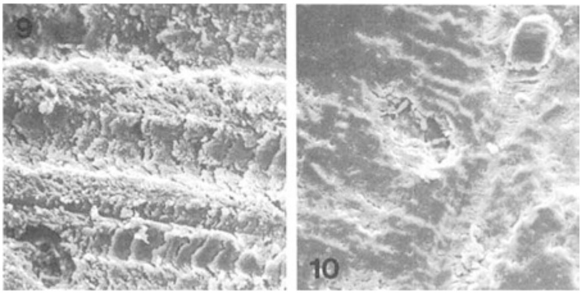


Fig. 16.12 SEM images of sliding abrasion. **9.** Fine particle-sliding abrasion cline. Field width, 60 μ. **10.** Coarse particle-sliding abrasion; field width, 60 μ. Note chatter marks on grooves. (From Bromage 1984:167, used with permission of T. Bromage and Elsevier)

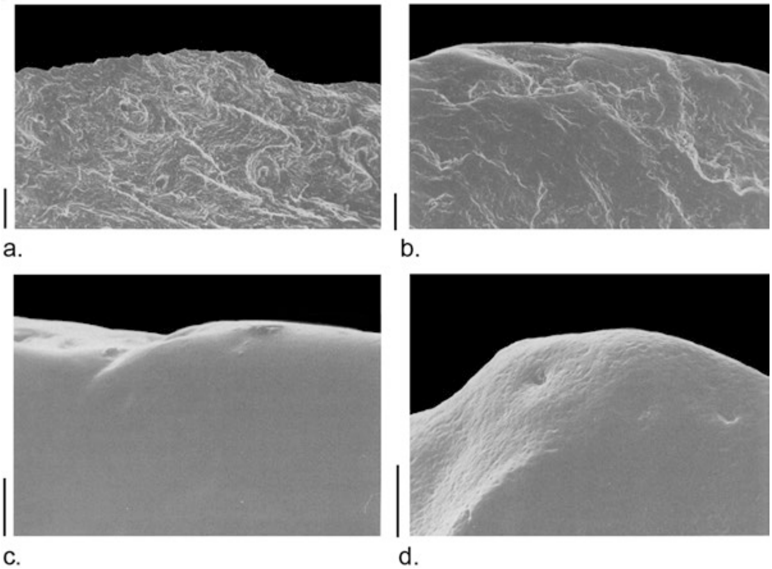


Fig. 16.13 Shipman's SEM micrographs of various abraded edges. **a.** Edge of experimental meat-cutting bone tool on a broken compact bone, before utilization, showing osteonal structure; **b.** Same edge after brief use, showing rounding of the working edge and obliteration of some but not all of osteonal and fracture features; **c**. Ethnographic hide-working tool, showing nearly complete obliteration of bone surface features, smoothing and polishing; **d**. Broken elephant bone abraded by fine sediment, showing polish similar to trampling, but distinguished by impact craters of the type shown by Bromage (1984). Black scale bar to left of each figure equals 100 microns. (From Shipman 1989: 320, Fig. 1, used with permission of P. Shipman and the Center for the Study of Early Americans, Texas A & M University)

Fig. 16.14 Sliding abrasion applied by humans to bone tool manufacture and use. Broken tip of an awl, probably used in basketry manufacture, recovered from an aboriginal site on the northern Monterey Bay coast, near Davenport, California. This image also illustrates the problem of covering bone surfaces with labeling fluids discussed in Chap. 8. (Photo by Don Harris of a specimen from the Monterey Bay Archaeology Archives, University of California, Santa Cruz)

experimental research on abrasion is that this surface modification can swiftly develop, even in contact with soft tissues, in a matter of minutes or hours. This implies that abrasion should be expected to be a common feature of human handling of bone during food processing, and not solely during tool manufacture and use.

Other studies have aimed more specifically at distinguishing bone tools from naturally abraded specimens. Shipman (1989) compared experimentally produced edge modifications to bone, ethnographic bone tool edges, edges produced by sedimentary abrasion in a lapidary tumbling machine, and by air-driven particles from a commercial abrader. As did Bromage's, Shipman's experiments indicated that very brief rubbing of bone against animal tissues starts to remove projecting features of the original break surface and begins the process of smoothing and polishing (Fig. 16.14). Much of the original break surface's low-relief features remained after such brief use. Longer use, as in cutting meat, produced an extremely smooth surface devoid of the original surface features, marked by occasional striae or angular pits. Shipman noted that similar features were seen on ethnographic bone scrapers used to remove flesh from skins. Shipman reported that experimental bones modified by water-borne sediments and by air-driven particles show the same microscopic pitting of the surface described by Bromage as characteristic impact abrasion.

16.4.3 Trampling

Trampling involves a form of sliding abrasion. Experimentally implicated in the production of trample marks (Chap. 14), trampling can also smooth and polish break surfaces and projecting edges of intact bone (Behrensmeyer et al. 1989).

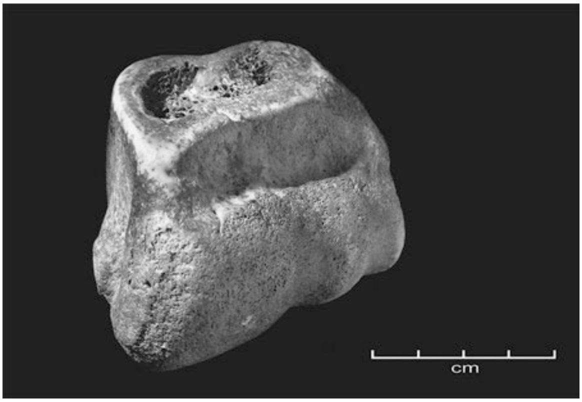


Fig. 16.15 Waterborne sedimentary abrasion, both impact and sliding abrasion in water: a distal cattle (*Bos taurus*) humerus, showing sawed surface overprinted by abrasion and removal of subchrondral bone on the articular. (Photo by Don Harris of material collected by the author)

Brain (1965) illustrated smoothing and polishing of broken sheep long bones trampled by livestock into the sandy substrate of a seasonal river in Namibia. He stressed that those unaccustomed to considering the range of possible actors and processes involved in abrasion could readily interpret such abraded breaks as intentional human tool production. Figure 14.8 shows some trampling abrasion on fracture surfaces.

16.4.4 Other Processes of Abrasion

Haynes (1991) reported that, in cases of animals surviving limb bone-shaft fractures for some days, broken ends of the element can be rounded and smoothed simply by rubbing together as the animal walks. This would be a form of sliding abrasion, perhaps also involving the effects of surrounding soft tissues (as in Shipman's discussion of meat polish on bone tools) and bodily fluids. As was reviewed and illustrated in Chap. 15, pot polish is sliding abrasion that may well be under-reported in zooarchaeological literature.

Thorson and Guthrie's (1984) study of bone fracture in ice cited in Chap. 11 also established that a mixture of ice and sedimentary clasts caught in it could produce abrasion on experimental specimens. Figure 16.15 illustrates the removal of subchondral bone and rounding of break surfaces effects by waterborne sedimentary impact abrasion, in this case the churning of the specimens in the surf zone at sandy beaches.

Behrensmeyer et al. (1989:116) discussed removal of bone tissues by airborne impact abrasion, or "sandblasting." The microscopic signatures of this form of impact abrasion would be the same pits noted by Bromage, but the removal of the outer bone lamellae is macroscopically notable. Bones subject to sandblasting modification become increasingly fragile and vulnerable to trampling or other

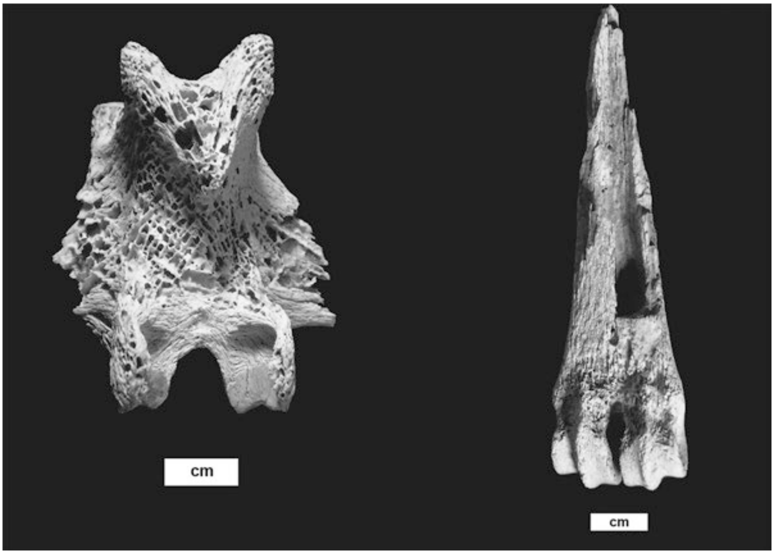


Fig. 16.16 Sand-blasting effects on a gazelle metacarpal (left) and a vertebra (right), after 10 years' exposure on a loose sandy substrate at Site 06, an ethnographic foraging site, near Koobi Fora, East Lake Turkana, Kenya. Scale: 1 cm. (Photo by Don Harris of material collected by the author)

mechanical damage or are ultimately are etched away. Figure 16.16 shows sandblasted elements exposed to windborne sediments for 10 years on a loose sandy substrate of a modern foraging site, near Koobi Fora, Lake Turkana, Kenya.

16.4.5 Sorting out Abrasion

Abrasion presents zooarchaeologists with interpretive problems because the same causal processes and effectors but different actors are involved in its production. The distinction between particle impact abrasion and sliding abrasion may help restrict the range of possible actors, especially given that most of the abrasive bone modifications caused by humans do not involve the former process. Nonetheless, because both nonhuman processes and human actors can cause sliding abrasion, this requires bringing in other lines of evidence – associated surface modifications, element or segment frequencies, associated contextual information – to determine a likely origin. For example, if one encounters mammalian diaphyseal splinters with striations, polishing and beveling on protruding tips only – and no traces of striations on other surfaces –associated with ceramic debris, human structural evidence, and other indicators of human food processing, it is more plausible to attribute the abrasion to pot polishing rather than ungulate trampling. This is yet another example of narrowing interpretive possibilities through juxtaposing of independent lines of evidence.

16.5 Geological Processes of Transport and Burial

Most paleontological treatises on taphonomy and paleoecology include extensive descriptions of sedimentary context, ascription of the agents of deposition, and their probable effects on vertebrate or invertebrate faunal samples. Because this book's main focus is archaeofaunal bone, geological processes of transport and deposition are less emphasized. However, such matters are certainly relevant to some archaeological cases, especially older deposits. Archaeological materials may be subject to eolian deposition, that is, burial in wind-borne sediments, to aqueous deposition, or burial in water-borne sediments, as well as various anthropogenic depositional processes such as secondary refuse disposal by dumping in middens, pits, ponds, etc. (Reitz and Wing 2008:112–114), or by human trampling (Gifford-Gonzalez et al. 1985; Villa and Courtin 1983; Villa 1982).

Geological processes have differential effects on bone survival and transport. While eolian sedimentation does not move elements of larger animals, blowing sand can abrade bone and shell to total destruction. Flowing water in seasonal streambeds, fluvial plains, lake margins, marine shorelines, even hilly slopes can either transport materials away from their original locales or bury them in place. Whether a skeletal element is transported or buried depends to some extent on its hydrodynamic properties. Zooarchaeologists with the greatest concern for aqueous transport as a taphonomic influence are investigators of Plio-Pleistocene open sites, where bone-accumulating processes have been controversial. However, one can imagine other, much later sites where vigorous water flow could differentially transport bones away from their original locations.

Paleontologists and zooarchaeologists have conducted laboratory and actualistic field observations on water transport of various sizes and shapes of skeletal elements. Voorhies (1969) undertook foundational work aqueous transport of vertebrate remains, using actualistic observations and circulating hydraulic flume experiments to shed light on his paleontological analyses. Voorhies experimentally established that various skeletal elements of one species possessed different potentials to be moved by flowing water. From his observations on deer and coyote bones, Voorhies defined three *transport classes*, groups of bones that moved similarly in response to flowing water (Table 16.2). He then used these empirically derived observations to assess the degree of winnowing in a dense Miocene bone concentration where elements of one artiodactyl species predominated.

Behrensmeyer and others (Behrensmeyer 1975; Gifford and Behrensmeyer 1977; Boaz and Behrensmeyer 1976) conducted experiments in the field and laboratory to explore factors underlying such transport classes and the behavior of anatomical elements from other species. Hydrodynamic properties of skeletal elements and molluscan shells that most influence transport are specific and gravity shape. Seilacher (1973) and Behrensmeyer (1975) stressed that bones are particular kinds of clasts, or sedimentary particles, of irregular shape. Behrensmeyer stressed that an element's specific gravity alone does not predict its behavior in flowing water, arguing that an element's surface-area-to-volume ratio as a key factor in

Table 16.2 Voorhies (1969:69) skeletal element transport groups, based upon experimental research with hydraulic flume. Note that there are three major groups with some elements displaying transport behavior intermediate. Voorhies mainly used complete elements of deer and coyote in his experiments, but note that the mandibular ramus, travels differently from the complete mandible

I	I-II	II	II-III	Class III
Move @ lowest flow velocity		Move @ higher flow velocity: by saltation on bottom		"Lag deposit" @ highest flow velocity: do not move, or moves in bed load
Rib	Scapula	Femur	Mandibular ramus	Cranium
Vertebra	Phalanx	Tibia		Mandible
Sacrum	Ulna	Humerus		
Sternum		Metapodial		
		Innominate		
		Radius		

determining its hydrodynamic properties. Relatively thin, flat bones have more "lift" in flowing water and are more likely to move farther. Lyman (1994) offers a critical review and analysis of this literature in his work on vertebrate taphonomy.

Before inferring human behavior from element frequencies, analysts working on archaeofaunas from situations where flowing water may have affected an assemblage should assess whether the elements conform to one or two of Voorhies' Transport Classes, that is whether aqueous winnowing could have affected the assemblage. A winnowed assemblage could resemble either the lag component or the transported component, ultimately deposited downstream or down slope from its original location. If this were the case, then considerable inferential caution is necessary. Since other processes, such as transport by humans or carnivores, could conceivably create equifinal element frequencies, contextual and bone-surface modification evidence would be critical to further addressing the question of what determined the observed patterning in element representation.

To assess the effects of geological processes, adequate documentation and analysis of sedimentary context are essential, including bedding structures and grain size analyses to assess rates of water flow. Lyman (1994) offers a detailed discussion of how archaeologists have applied this and other paleontological approaches to assessing the degree of fluvial transport from assemblage content and context.

16.6 Diagenesis: Not Just for the Deeply Buried

Diagenesis denotes the transformation of sediments, organic remains, or trace fossils into mineral bodies. For vertebrate remains, one end of the preservational spectrum is continued existence through replacement of the original bioapatite by other minerals, especially fluorine compounds, plus perfusion of natural pore spaces with exogenous minerals. At the other end of the spectrum is destruction by a combination of biotic, chemical, and mechanical processes. Actual specimens often lie somewhere along this spectrum. In some specimens, much of the element's original osteonal organization is retained, a level of preservation that has enabled paleontologists to investigate dinosaur bone histology. In other specimens, diagenetic processes preserve an element's overall form, but microscopically, the original crystalline structure of the living bone has been utterly reorganized, or "erased," by diagenesis (Sillen 1989).

Diagenetic effects are relevant to zooarchaeologists for at least three reasons. First, researchers wishing to study the stable isotope signatures of feeding adaptations must distinguish between isotopic ratios produced by dietary intake during life and those strongly influenced by diagenesis (Lee-Thorp and Sealy 2008). The literature on chemical aspects of bone diagenesis in these areas has proliferated, and this will not be explored in detail here. Interested readers are referred to relevant reviews (Koch 2007; Sillen 1989; Sillen et al. 1989; Lee-Thorp and Sealy 2008). Second, ancient DNA investigators must be aware of post-depositional effects, especially the action of microbes, on genetic material (Turner-Walker and Jans 2008). Third, some new findings on bone diagenesis are relevant to vertebrate remains commonly encountered by the majority of zooarchaeologists: bone that is not highly mineralized, sometimes called "subfossil." This section concentrates on the latter.

Processes that combine to modify and preserve bones are, to quote a noted bone diagenesis researcher, "complicated" (Hedges 2002). However, actualistic research with bone assemblages on land surfaces, plus controlled comparisons of large samples from archaeological sites have substantially revised earlier perspectives on diagenesis and suggested some general factors that simplify this complexity.

Paleontological taphonomists formerly divided the postmortem existence of organic remains into biostratinomic and diagenetic zones or phases (Lawrence 1979a, b). By analogy with diagenetic processes affecting sediments, researchers assumed that mineral replacement and other transformations in bones occurred well after burial in sediments, which offered a very different chemical environment than that of bones on a land surface (Rolfe and Brett 1969; Wyckoff 1972). Research has now demonstrated that, in some environments, shallowly buried or even unburied mammal bones undergo mineral deposition and geochemical transformation within a few years of death (e.g. Tuross et al. 1989; Trueman et al. 2004). Moreover, and perhaps most relevant to zooarchaeologists working with largely unmineralized vertebrate remains, researchers have concluded that the ultimate preservation or destruction of skeletal elements is determined during the first few months of their postmortem existence. Bioerosion has been shown to strongly influence bone survival across many different sedimentary environments.

To appreciate why this could be the case, some basics of postmortem bone survival are necessary. Calcium hydroxyapatite is highly soluble, and its calcium ions tend to be replaced by those of other minerals, especially fluorine, forming fluoroapatites (Sillen 1989). In life, bone's high vascularity and bioapatite's solubility allows swift bone remodeling or mineral infusions to the blood (Chap. 4). After death, these same properties that made bone a dynamic, adaptable tissue in life can enhance its destruction. However, a critical period of protection exists: Trueman and Martill (2002) note that bioapatite would readily dissolve in groundwater postmortem, were it not for the buffering effects of collagen, while microbes' collagenase molecules, which could digest bone collagen, are too large to penetrate skeletal elements' bioapatite structure. This creates a temporary "state of mutual protection, affording greater stability to both components in burial environments" after a vertebrate's death (Trueman and Martill 2002:372).

According to the chemical and biotic environment of a skeletal element, this stability is some point disturbed. From then on, interactions that lead to divergent outcomes are set in motion, one leading to destruction of the skeletal element and recycling of its constituents in the ecosystem, the other leading to the transformation of formerly living tissue into a rock-like structure that mimics its living form. Jans (2008) describes long-term preservation as cases when collagen breakdown by bacterial enzymes or other forms of hydrolysis is sufficiently slow to that conversion of bioapatite into more stable crystals can occur. Because mineralization can be swift or slow according to microenvironmental chemistry, and collagen hydrolysis rates can also vary, preservation is favored by a range of conditions, rather than at a set "magic number." An extreme example of bioapatite's dissolution in an acid matrix with preservation are skeletons of the leathery "bog people" bodies of northern European *Sphagnum* wetlands (Turner-Walker and Peacock 2008), where mainly bone collagen remains. Either extreme in environmental pH compromises bone survival; more acid environments dissolve bioapatite, while more alkaline environments accelerate collagen breakdown and the literal disintegration of an element (Fig. 16.8). Many zooarchaeologists have encountered pits and loss of cortical bone due to chemical erosion in soils. While stomach acids may pit bones consumed by predators, alkaline soils can also pit, corrode, and otherwise alter periosteal and fracture surfaces. Andrews (1990:19–22) illustrates and discusses chemical effects of soil and water on bone surfaces in comparison with those produced by carnivore action. See also Fernández-Jalvo and Andrews (2016:Chap. 8) for an illustrated comparative discussion of corrosion processes. Bochenski & Tomek (1997) report on experimental comparisons of alkaline soil vs. stomach-acid erosion in birds.

Jans et al. (2004) carried out a regional-scale study of types and causal agents of bioerosion in 261 archaeofaunal skeletal elements (mainly bovine long bones but also some human elements from burials) from 41 Holocene sites (c 6000 BP to 200 BP). The sites were located in arid to moist environments in southeastern to northwestern Europe (see also Smith et al. 2007). Cross-sectional samples of bone were documented using multiple, previously developed criteria for indexing diagenetic transformation, as given in Table 16.3. The resulting data were analyzed by Principal Component Analysis (PCA).

Jans et al. (2004) found that 68% of all specimens had undergone some microbial attack, and of these, 85% appeared to reflect bacterial rather than fungal attack, with linear-longitudinal and budded MFD's being the most common. Using mercury intrusion porosimetry (HgIP), they established that non-Wedl type tunnels display an enlargement of natural pores to 0.1–10 microns, consistent with bacterial average

Table 16.3 Variables recorded in the comparative study of bioerosion and preservation of archaeofaunal bone in Holocene European sites (Smith et al. 2007; Jans et al. 2004)

1.	Percentage of collagen relative to a fresh bone standard.
2.	Mineral crystallinity index as diagnosed by Fourier transform spectroscopy (FTIR).
3.	Mineral carbonate/phosphate (C/P) ratio relative to a fresh-bone standard.
4.	Oxford histological index based on percent of original bone tissue structure remaining.
5.	Cracking index, the percentage of osteons that are cracked.
6.	One of three measures of porosity, according to pore size range, measured by mercury intrusion porosimetry, with the assumption that largest pores are likely bioerosion products.
7.	Bulk density, including interstitial and pore volume, as measured by mercury intrusion porosimetry.
8.	Skeletal density (density of the material, excluding connected pore volume), as measured by mercury intrusion porosimetry.

Table 16.4 Four preservation types isolated by Principal Component analysis, PC1: Extent of Degradation; PC2: Type of Degradation (Smith et al. 2007; Jans et al. 2004)

1	**Well-preserved (WP) specimens.** These specimens tend to have a high Oxford histological index, high C/P ratios, low crystallinity, and low porosity values. All measures approach those of modern bone.
2	**Accelerated collagen hydrolysis (ACH) specimens.** These specimens tend to display a low collagen percentage and highly altered mineral (high crystallinity), correlated with a lower C/P index (0.1) compared to modern bone. However, this set showed good histological preservation, despite a high cracking index. This group's porosity values displayed increases in the small pore range relative to that of modern bone (Smith et al. 2007), resembling bone deproteinated in the laboratory or boiled for over 24 hours.
3	**Microbially attacked (MA) specimens**. These bones tend to have decreased OHI scores and increased porosity in the "medium" range, >0.1 mm <8.5 mm diameter but low cracking index and low small porosity. The group tends to have lower collagen values. Histology reveals replacement of original bone structure with microbial pores or tunnels.
4	**Catastrophic mineral dissolution (CMD) specimens.** These have high values of the largest, >8.5 mm to ~70 mm, diameter, along with low bulk density and % collagen, low C/P ratio, and high IRSF values.

diameters (Jans et al. 2004:87). Contrary to expectations based on the many variables and highly diverse environmental settings of the samples, PCA indicated just four diagenetic factors accounted for over 60% of the variation in the sample. The researchers used highly significant positive and negative correlations within their correlation matrix to characterize four types of bone specimens, as outlined in Table 16.4. The authors contended that the fourth, CMD category were elements that were actually in the process of slowly dissolving when they were recovered. They speculate that a positive feedback relationship exists between microbial pore space enlargement and further dissolution of bone around the pores by groundwater intrusion. Somewhat counter-intuitively, archaeofaunal specimens proved to be generally *less* susceptible to microbial attack, and therefore more likely to survive over the long run, than are skeletal elements in human burials or interred whole animals. They speculate that, because elements in buried bodies were not quickly dissociated from their bacteria-rich circulatory systems, bioerosion made quick headway after death and burial.

The Jans et al. (2004) study produced several important take-away messages for zooarchaeologists. First, despite a great diversity of sites, climates, soil conditions, and ages, preserved, subfossil bone samples displayed only a few systematically related conditions. Second, the role of microbial bioerosion in bone diagenesis is considerable, as it enlarges pore spaces in bone tissue that can be further enlarged – and the bone further compromised – by acidic groundwater. Third, if microbial remodelling is a major path toward bone destruction, archaeofaunal specimens appear to have better odds of survival. However, the latter finding should be set into the broader context of longer-term preservation via mineralization. Trueman and Martill (2002) report that the paleontological bones they examined displayed a statistically significantly lower rate of MFD alterations than the reported rates for archaeofaunal bone specimens.

16.6.1 Effects in and on the Soil Zone

Sillen (1989:214–218) notes that in some fossil bone, the bone mineral apatite component becomes more crystalline during mineralization, with average crystal size increasing, a process also noted during heating experiments (Chap. 15). Fluorine, a common mineral in groundwater, can permeate buried bone and replace the calcium ions over time, resulting in a more durable variant of hydroxyapatite. The gradual increase in fluoridated apatites in bone has been used to assess whether bone specimens are truly contemporary with one another, as was the case in exposing the Piltdown hoax by showing the cranial and mandibular specimens differed markedly in their fluorine levels (2002).

Wedl tunnels and non-Wedl, MFD tunnels convey mineral-rich fluids into the bone pore spaces, which can precipitate as crystals. Calcite is a common crystal found in pore spaces (Oakley 1964). Moreover, MFD spaces are mineralized along their edges with carbonates, sulfides, or iron oxides.

Trueman et al. (2004) collaborated on analysis of bones of nine individual ungulates, ranging in size from wildebeest to elephant, monitored on land surfaces in the Amboseli National Park, Kenya by Behrensmeyer from 1975 to 2001, inspecting the bones for microbial bioerosion and mineralization. Microbial erosion was relatively rare in these animal specimens, but roughly half of the carcasses had authigenic mineral deposits within the bones, including calcite (the most common), barite, crandallite, dahlite, trona, and (Trueman, et al. 2004:Table 1). The authors' actualistic research demonstrated that bones lying on a generally alkaline soil surface for 26 years or less begin to accumulate mineral deposits in their interior spaces. Although weathering processes ultimately destroy most skeletal elements in the Amboseli landscape, this study shows that the path toward mineralization can begin even before deposition.

Readers wishing to further explore bone surface modifications from such actors and processes should consult Fernández-Jalvo and Andrews (2016) for their profusely illustrated treatment of many of these.

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Part V

Studying Behavioral, Social, Ecological Contexts

Chapter 17
Analyzing Multi-Agent Assemblages

The topics covered in this and the following chapters shift from the relatively straightforward identification of effectors and actors summarized in Part IV to inferring past behavioral, social, and ecological contexts in which such evidence was produced (Fig. 3.2). How animal remains can shed light on the place of humans in regional ecosystems, on human social relations, on commodity production and exchange, or on ritual life encompasses most zooarchaeological researchers' ultimate interests. However, such questions present much greater inferential challenges and are more subject to debate among practicing zooarchaeologists, as the chapters of this section will outline. As noted in earlier chapters, the most commonly used faunal evidence for addressing these issues is the *aggregate patterning* of bone modifications and element frequencies, as interpreted in the context of other archaeological evidence as well as geomorphic and geological context.

Moving toward such levels of interpretation rests on the assumption that human actors produced the aggregate evidence. However, one seldom encounters vertebrate archaeofaunas accumulated and affected by only one actor or process. Even with relatively recent historical samples, scavenging birds and mammals, gnawing rodents, trampling, weathering, and other post-discard processes can influence element frequencies and overprint human bone surface modifications. Zooarchaeologists face the challenge of teasing out the dominant agents involved in "multi-agent accumulations," the sequence of their effects on a sample, and those effects on various properties of the remaining assemblage. They are not alone. Paleontological taphonomy emerged in response to parallel challenges in the use of data from fossil deposits to infer species paleobiology and paleoecological relations of multiple species in deep time. For zooarchaeologists working with samples where multiple agents appear to be involved, vertebrate taphonomists' analytic approaches are valuable resources that will be discussed at the end of this chapter.

When evidence suggests that assemblage formation involves multiple actors, one must consider what constitutes relevant and credible evidence for the action of any one of these. Referring to early sites with sparse archaeological evidence, Binford (1981) and Brain (1976, 1981) argued that spatial association of human

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artifacts with vertebrate remains is not a sufficient basis for inferring that hominins were the principal actors responsible for creating a faunal accumulation, nor is non-random patterning in fracture and bone surface modification. These insights hold true for much later sites as well, where nonhuman actors and processes can introduce or restructure archaeofaunal materials. Part IV recapitulated four decades' actualistic research aimed at specifying the distinctive effects of various actors and effectors.

In determining which actors and processes could have created assemblage structure, a prudent first step is to consider the range of such agents possibly involved, and then to narrow this range, excluding actors and processes that would most likely *not* have been involved in creating the assemblage. This is facilitated by distinguishing which of these potential agents could be both bone accumulators and bone modifiers, which modifiers were not accumulators, and whether any accumulators would not have been modifiers. Certain actors and processes can be excluded from one of these options, simply based upon a priori knowledge of their capabilities. If, for example, in a cave site excavation yielding many bison elements that display heavy gnawing by rat-sized rodents, one would be unlikely to attribute the *accumulation* of the bison bones to those rodents. One would instead seek biological actors or geological forces powerful enough to have accumulated these large and heavy objects. Cave geomorphology and sedimentology could be evaluated to assess whether the cave may have been a natural trap into which bison fell without any human intervention (e.g. Oliver 1989), or whether, given the placement of the cave mouth, the bones could have washed into it with heavy precipitation. If these options appeared unlikely, one could turn to bone surface modifications that testify to action of humans or larger carnivores – or both – capable of carrying bison parts to the cave. This process thus involves arguing from first principles in a kind of dialogue between the analyst and the assemblage, using available evidence and a background knowledge of causal relations like those covered in Sect. IV to discern modifying actors and processes and to assess what kinds of effects each could have on the sample.

The approaches outlined in Chaps. 19, 20 and 21 involve using criteria derived from actualistic research to distinguish the effects of different actors and processes on vertebrate remains. After identifying the most probably implicated actors or processes, it is useful to specify which among these could produce equifinal outcomes in one line of evidence – such as element frequencies – while leaving other, more distinctive, traces, such as tool, tooth, or trampling marks as bone surface modifications. Explicitly stipulating actors or processes that produce equifinal outcomes in one line of evidence permits one to identify other, independent lines of evidence to evaluate the likelihoods of their actions on the sample under analysis. The goal of these steps is not necessarily to "prove" the action of a given actor, but rather to stipulate which are the most and the least likely to have produced the patterns in the observed archaeofaunal evidence. This may seem a simple-minded, "paint-by-numbers" exercise, but considering and eliminating the obvious can be a useful exercise: specifying why an agent is being eliminated from consideration sometimes forces a reexamination one's base assumptions. Despite such approaches, the dominant agent or agents responsible for an archaeofaunal sample's constitution may be ambiguous. Nonetheless, getting to that conclusion systematically enables one to assess how – and even if – the sample can be used to draw inferences about human behavior. The issue of whether some assemblages are better than others at doing so will be addressed in the Egeland et al. (2004) example presented below.

The following sections present some cases that illustrate how zooarchaeologists have worked through identification of the dominant actors and processes in multi-agent deposits, all using multiple, independent lines of evidence and actualistically derived knowledge of hominin and nonhuman actors' and processes' effects. These case studies are not an exhaustive list, but they illustrate how the actualistic research outlined in Part IV is mobilized to explicate the effects of more than one actor or accumulating process. As might be anticipated from prior chapters, several cases are from palaeolithic zooarchaeology. and one derives from the Americas, employing an approach pioneered in paleontological taphonomy that may be applicable to other zooarchaeological cases. In doing this, my interest is not so much whether the authors are "right" in their broader inferences about hominin behavior as in *how they used zooarchaeological knowledge* to work through the questions they faced.

17.1 Working to Identify Actors and Contexts: Some Pleistocene Cases

Actualistic research by paleoanthropological zooarchaeologists has contributed to methods for clarifying the origins of multi-agent assemblages, regardless of their antiquity. Plio-Pleistocene vertebrate archaeofaunas often present scant and ambiguous evidence for hominin agency. Some research has focused on defining distinctive signatures of "hominin first" or "carnivore first" processing of medium- to large-sized ungulate elements, especially long bones, which preserve carnivore tooth marks and marks of human cutting and percussion. To recapitulate, hominins use percussion on diaphyses to open long bone marrow cavities, leaving epiphyses largely untouched. By contrast, carnivores attack epiphyses, regardless of whether or not they have first access to the elements or are scavenging human discards. In cases where marrow was still enclosed in diaphyses, carnivores will gnaw and compress the shafts, seeking to collapse them and in the process leaving tooth marks on diaphyseal surfaces. However, experiments suggested that, when marrow had previously been removed, carnivores did not gnaw diaphyses or shaft fragments. Given the ubiquity of carnivore species, including bone-consumers, in contemporary and paleontologically documented African ecosystems, zooarchaeological researchers believed it most prudent to focus their analytical attention on diaphyseal fragments, because these are the most likely parts of the postcranial skeleton not only to preserve but also to display the presence or absence of "overprinting."

17.1.1 What Created the Assemblage? Disentangling some African Early Stone Age Palimpsests

Building upon these actualistically derived understandings, a group of researchers who have worked on Early Stone Age (ESA) deposits in southern and eastern Africa Egeland, Pickering, Domínguez-Rodrigo, and Brain (2004) undertook a comparative assessment of mammal bone assemblages known to incorporate some carnivore and hominin modifications. Their goal was to distinguish "the level of functional independence of the hominin- and carnivore-derived portions from several important Plio-Pleistocene archaeofaunas" (Egeland et al. 2004:343). They used experimentally derived understandings of bone surface modifications to assess whether hominins and carnivores had left marks of their intervention on the same specimen and, by extension, whether these actors had interacted with components of a single carcass. Such a co-occurrence implies a close temporal association of the respective species' nutrient-seeking behaviors.

Rather than focus a priori on the *sequence* in which carcass parts were handled by the potential consumers, they chose to characterize the formation of an assemblage in terms of the *degree of overlap* of different consumers' bone surface modifications in each sample. In doing so, they aimed to develop a replicable method for sorting highly independent from highly interdependent assemblages, with the ultimate goal of defining assemblages in which the majority of elements appear to have been modified by one dominant actor, especially hominins. This in turn would enable a warranted set of inferences about hominin carcass processing. In other words, the authors aimed to construct a reliable approach to assessing what proportion of an assemblage reflected the operational chains exclusive to one or another set of actors (Chap. 15). They focused on marks typifying the "carcass or bone modification phase" of assemblage formation and chose mid-shaft, diaphyseal specimens as those most likely to preserve signatures of the original processors. "We argue that the frequency of limb bone specimens that preserve evidence of both hominin (cutmarks, percussion marks) and carnivore (tooth marks) involvement can serve as an estimate of hominin-carnivore overlap in assemblage modification" (Egeland et al. 2004:346).

Egeland et al. used actualistic documentation to create statistical expectations, expressed as a simple % average with 95% confidence intervals, for tooth and cut marks on the same element, for tooth and percussion marks on the same element, and for, tooth marks plus cut- and/or percussion marks. They applied this to their own research data plus published zooarchaeological information for FLK 22 *Zinjanthropus* ("FLK *Zinj*") from Bed I, Olduvai Gorge, Tanzania (see references in Egeland et al. (2004), also Chaps. 14–16), Monahan's (1996) Olduvai Bed II faunas from BK, MNK Main, and HWK East Levels 1–2, the ST Site Complex at Peninj, also in Tanzania, Swartkrans Member 3 (see references in Egeland et al. 2004). Details of what constituted a comparable selection of diaphyses for each site assemblage may be read in their article. They then tabulated the percentage of NISP in these assemblages that displayed at least one tooth mark and at least one cut mark, or at least one tooth mark and at least one percussion mark.

The results indicate that the percentages of both tooth and cut marks on specimens from Olduvai Bed II, Peninj, and Swartkrans Member 3 were "below those expected if their hominid- and carnivore derived components were modified under a high degree of interdependence" (Egeland et al. 2004:349). By contrast, the much-discussed FLK *Zinj* sample was within the range or above the mean for actualistically derived assemblages with both carnivore and hominin involvement. The authors remark that the Swartkrans Member 3 assemblage is especially interesting because, although carnivore-modified diaphyses outnumber those with hominin modifications three-to-one, these are generally independent of each other. As they put it, "The Swartkrans Member 3 fauna thus promises to be an extremely useful datum for understanding hominin carcass foraging in a relatively 'uncomplicated' taphonomic context… considered separately from the carnivore-modified component" (Egeland et al. 2004:349). Similar conclusions were drawn regarding the aggregate of Peninj "mini-sites" and the Bed II faunal samples from Olduvai. Thus, the method appears to efficiently identify assemblages best suited for studying early hominin carcass processing, and one can imagine permutations of it could be applicable to other contexts and cases.

17.1.2 What Created the Assemblage? Die Kelders 1 and the Middle Stone Age

Marean and coworkers (2000) published an extensive analysis using context, species and element representation, and bone surface modifications to sort out the dominant accumulating actors and processes at Die Kelders 1, a coastal South African cave containing extensive Middle Stone Age artifact assemblages, especially in Levels 10 and 11. Using Capaldo's (1997) distinction between the "nutritive" and "non-nutritive" phases of the taphonomic histories of vertebrate remains, they argued that post-nutritive processes can displace, weaken, break, or destroy skeletal elements originally accumulated in a deposit, thereby affecting the collection's potential for elucidating about hominin or other creatures' nutritive behavior. They stated their ultimate goal as, "identifying the impact and consequence of non-nutritive processes, so that we can evaluate the integrity of the DK1 fauna for investigating hominin behavior and identify those aspects of the assemblage likely to be sensitive to hominin behavior" (2000:207). This is of special interest to paleoanthropologists because the South African MSA is associated with very early modern humans.

To assess the usefulness of the Die Kelders 1 faunas for studying hominin behavior, Marean et al. first sought to identify the dominant accumulator(s) of the deposits using previously published data on the vertebrate assemblages as well as reasoning from actualistic datasets. In much the same process of elimination advocated earlier in this chapter, the authors begin by stipulating the range of possible bone accumulators and their signatures. These included African porcupines, large raptorial birds, carnivores, especially the brown hyena, and hominins. They excluded porcupines and smaller rodents as accumulators because of the very low rates of gnawing in the aggregate assemblages, given documented high rates of distinctive gnawing in rodent-accumulated samples. With regard to large avian raptors, they concluded that these had a significant effect on accumulating both molerats and very small bovids. The avian scenario is supported by the spatial distribution of gastric-etched bones fragments, which cluster toward the front of the cave near where solution holes tend to develop. These, the authors argue from modern analogy, would have provided roosts for raptors. The authors used the degree of gastric acid etching on the bone specimens of these two taxonomic groups as an index of non-hominin involvement during the nutritive phase, further excluding the likelihood of involvement of larger carnivores such as jackals and hyenas because of the lack of gastric etching on bones of larger-bodied taxa. Hyenas, for example, would have been as likely to swallow – and later vomit up – bones and bone fragments of the larger sizes of bovids as the very smallest.

Larger mammal carnivore tooth marks were common on Layers 10 and 11 specimens. However, so are percussion-marked diaphyses typical of hominin marrow processing. The authors worked through this confounding set of "signals" as follows. Percussion-marked diaphyses are precisely the types of shaft fragments in which carnivores are not interested, so their abundance reflects hominin accumulative activity at Die Kelders 1. Marean et al. examined tooth marks rates on diaphysis fragments of different-sized bovids, showing that these increase with size class. Returning to the actualistic data recapitulated at the outset of this section, Marean et al. (2000: 214) noted that the relatively low incidence of carnivore tooth marks on mid-shafts "closely resemble[s] a situation where 100% of long bones were hammer-stone broken, discarded by hominins, and then ravaged by carnivores." They further noted that comparisons of MNE estimates for different long bone segments supports this scenario because epiphyses are much less abundant than are diaphyses.

However, the authors noted that the percentage of long bone fragments with *both* percussion and tooth marks in Layers 10 and 11 is 1–2%. Citing these data, they state that,

> ...a portion of the toothmarked fragments probably were contributed by carnivores without prior processing by hominids. However, given the low overall frequency of tooth marked long bone fragments… we can confidently state that only a small percentage of long bone fragments could have been accumulated by carnivores (Marean, et al. 2000:216).

Turning to post-nutritive taphonomy, Marean et al. developed an argument based on their elaboration of Villa and Mahieu's (1991) break-edge angle/break-surface analysis (Chap. 12). They note that specimens displaying weathering in Layers 10 and 11 are rare, thus eliminating subaerial weathering as a contributing factor in assemblage fragmentation rates. Many specimens are burned and display differentially more right angle and transverse breaks. If burned specimens are deleted from tabulations, Layers 10 and 11 have few dry-bone breaks, relative to fresh breaks. Given these combined lines of taphonomic evidence, the authors argued they can use Layers 10 and 11 as a basis for studying humans' selective transport of different-sized ungulates' body segments.

17.1.3 Actualistic Notes on Human Habitations as Scavenger Magnets: Overprinting Likely

Marean and coworkers' scenario for intensive carnivore consumption of hominin bone debris may seem only likely in the remote past, when humans foraged in ecosystems full of large carnivores. However, researchers working with modern and relatively recent settlements in Africa, Southwest Asia, and South Asia have documented the persistence of scavenging carnivores, and their impacts on human refuse and burials, augmented by feral domestic dogs (Horwitz and Smith 1988; Lotan 2000; Monchot and Mashkour 2010) (Chap. 12). In regions where large, bone-crunching carnivores persist, the likelihood of carnivore "overprinting" is confined neither to forager sites nor to the remote past.

Site 105, the Dassanetch settlement mentioned in Chap. 15, was a relatively large defensive encampment created during a drought in 1973 and abandoned after about 6 weeks (Gifford-Gonzalez 1989). About a month later, I documented the site and collected about 2800 faunal specimens of cattle, sheep, and goats, fishes, crocodiles, and turtles, and at least three common zebra (*Equus quagga burchelli*) for further analysis. The dominant agent accumulating the Site 105 fauna was never in question. To my surprise, however, I found the rate of carnivore gnawing on Site 105 mammal specimens was five times higher than that documented for carcasses of 48 wild zebra, topi (*Damaliscus lunatus*), and oryx (*Oryx gazella*) that I had been monitoring from the time of their deaths, over the same time span and in the same area. Carnivore tooth marks were found on 5.5% of 105's mammal specimens, one month after the site was abandoned, versus on 1% of the aggregate sample of natural ungulate death specimens within the first month postmortem. It was possible to infer the sequence of bone processors by noting the location of human-generated damage (cuts, chops, impact fractures, thermal alteration) in relation to where carnivore gnawing occurred. The overall inference is the same as that drawn by Marean et al. for Die Kelders 1 Layers 10 and 11: carnivore impacts occurred *after* human processing. Few domestic dogs were left in the region in 1973 after a state-sponsored rabies eradication program. Specimens bore tooth marks of large carnivores, and some clearly of hyena-sized teeth (Fig. 12.5). Spotted hyenas were in evidence, although sparsely, in the region during this time.

Human sites may serve as "magnets" for carnivores scouting scavenging opportunities. These are more concentrated and certainly more spatially predictable food sources than are chance encounters with single animal deaths or small prey in semi-arid environments. Such a "magnet effect" could lead to higher intensities of carnivore modification in these assemblages than on bones dispersed throughout the landscape. Domestic animals are generally fattier than wild ones, although cooking removes fats and other nutrients from bone (Lupo 1995). The "magnet effect" documented by Marean et al. and myself for very different times and adaptations highlights the complexities of site formation and the effects of successive bone modifiers, even in modern human situations and merits further study in other contexts. Mobile foragers, such as those who created Layers 10 and 11 at Die Kelders 1 or mobile pastoralist-foragers who set up Site 105 create scavenging opportunities upon leaving a locality. This point was also made by Mondini (2002) with reference to South American rockshelters (see below). These results influence how I interpret the taphonomic histories of early pastoralist archaeofaunas in East Africa that are only a few thousand years old but were deposited when and where multiple bone-modifying wild carnivores, as well as domestic dogs, existed. More permanent human settlements may be part of regional scavenger ecology, as they are today in parts of Africa and the Near East, and researchers should consider how to detect the possibility and nature of their effects on archaeofaunas.

17.1.4 What Created the Assemblage: Yarimburgaz Cave, Turkey

Stiner, Arsebük, and Howell (1996) explored the roles of several actors, including bears, other carnivores, and hominins, in forming a cave accumulation. Yarimburgaz Cave is a limestone cave with stratified deposits containing numerous remains of the Pleistocene cave bear, *Ursus deningeri,* an earlier cave bear species than the better-known *U. spelaeus*. These were associated with sparser remains of ungulates and other carnivores, as well as over 1600 Middle Paleolithic artifacts. Over 90% of the 4180 macromammal specimens recovered were attributed to *U. deningeri*, and the remainder derived from a variety of hoofed herbivore species (NISP=151), lion and possibly leopard, two species of small cats, spotted hyena, wolf, fox, jackal, possibly a dhole (a Eurasian wild canid), and a small mustelid (total carnivore NISP=109).

In assessing accumulating actors and processes, the authors first used cave geomorphology to eliminate flowing water as a possible bone transporting mechanism during the span the cave accumulated bones. Biological actors are more likely, and, unlike carnivore taxa discussed in earlier examples, bears are likely to "self-accumulate" through their hibernation habits. Stiner et al. reviewed wildlife literature on living bear species, to identify physiological and behavioral features that can be assumed to hold for Pleistocene members of the Ursidae. With the exception of the polar bear, ursids are omnivorous and do not collect food in their hibernation dens, though they may amass piles of vegetation for bedding. They are extremely vulnerable during hibernation, and dens where they sleep are usually hidden, in terms of their visibility and the lack of olfactory clues to their location.

Stiner and colleagues explored the spatial effects of denning bears on materials in caves, skeletal element profiles, bone surface modifications, and the age structures that one might expect from hibernation deaths. In documented contemporary bears, these deaths result from starvation and peak toward the end of the winter, although bears that deplete their reserves may wake and attempt to forage. Bear deaths in dens contribute entire skeletons to a cave floor, but, as Stiner et al. (1996:291) succinctly put it, "Whereas hibernating bears are nearly odorless, a dead bear is not and therefore is likely to attract scavengers once the carcass is abloom" A redolent carcass would attract large and small scavengers, including other hungry bears, contributing to scattering and destruction of skeletal parts, as well as bone surface modifications by consumers. Today, wolves and male bears are the most common consumers of dead or hibernating bears. Age classes most affected by hibernation are immatures, which may die soon after birth or during their first or second winters due to lack of adequate foraging and fat deposition, and old adults. This creates a classic "attritional," or U-shaped, age structure, low in representation of older juveniles and adults (Chap. 22).

From these contemporary facts, the authors framed expectations about an assemblage produced primarily by hibernation deaths, through starvation or predation and/or scavenging. They proposed that the representation of ungulate skeletal elements would differ from that of bears because the ungulates were likely to have been accumulated by non-ursid carnivores temporarily using the cave. The Yarimburgaz bear sample's spatial organization, skeletal element representation, and bone surface modifications are examined to assess whether they matched each of these expectations.

To explore how much bears' skeletal element representation reflected *in situ* destruction, Stiner et al. compared MNI calculated from skull landmarks with MNI estimated from teeth, reasoning that both were initially present as components of the cranium or mandible, and that nutritive-phase transport would therefore affect both equally. They argued that the divergence of the respective MNI statistics could enable assessment of the extent of *in situ* destruction, as these two components of cranial units have different durabilities. In all but one sample, tooth-based bear MNI estimates is twice as great as MNI estimates from cranial bone landmarks. A very similar ratio of tooth to bone is also seen in a comparison of MNE and MNI derived from small dense bones (e.g. carpals, tarsals, patella), limb bones, and cheek teeth (Stiner, et al.1996:296).

Carnivore tooth marks on bear skeletal elements occurred at a different rate (10%) than it did on the rarer ungulate remains (19.7%) or even on those of carnivores (18%), suggesting that remains of these three mammal groups had followed divergent postmortem taphonomic pathways (Stiner, et al. 1996:302). The authors reported that tooth marks reflect larger-bodied carnivores, and that some tooth marks in trabecular bone (see Chap. 12) are clearly from wolf-sized canids. However, four young bear bones show even larger marks, possibly reflecting ursid-on-ursid cannibalism. Acid etching on both infant bear remains and those of other species, including hares, which were recovered in spatial association, most likely are fecal deposits from large canids, rather than hyenas, which do not pass such bone fragments through their digestive tracts. The authors argued that, because modern carnivores accumulate and gnaw remains of ungulates and of their ambushed carnivore competitors, the higher incidence of tooth marks on these elements implies that such carnivores as wolves and, possibly, hyenas used Yarimburgaz Cave as a den or resting locality.

Rodent-gnawed bone specimens show the inverse pattern, with bear metapodials and phalanges being more frequently and intensively gnawed by vole-sized animals than are those of other taxa. Stiner et al. noted that weathering is little advanced on any mammal bone elements, as expectable in a protected cave environment, and that disparate sample sizes confounded assessment of whether weathering rates for bear elements actually diverge from those of other species.

The age structures of the Yarimburgaz cave bears were assessed on the P^4, M^1, M^2, M_1, M_2, and M_3, using Stiner's ternary plot format, with frequencies of Juveniles, Prime Adults, and Old Adults plotted at each point (Chap. 22). Overall, these reflect a U-shaped mortality pattern, "entirely consistent with the hibernation scenario" (Stiner, et al. 1996:313).

Hominin-modified ungulate bones are very rare, but a few cut marks were documented. No burning was represented, nor can the sizes of the loading point notches unequivocally eliminate carnivore' static loading. The spatial distributions of ursid, ungulate, and non-ursid carnivore bones, plus stone artifacts, appeared to display no preferential clustering by class, which the authors attributed to a combination of very slow sedimentation rates and, probably, bear bedding behavior as a source of mixing (Stiner, et al. 1996:305). This impression was assessed using a Pearson's (r) correlation matrix. This showed no discernable difference in the samples with bear and lithic abundances above zero, in the association of bear remains with those of ungulates and carnivores, reflecting the general impressions of excavators. However, this statistical exploration produced an unexpected, mutually exclusive relationship between ungulate remains and lithics, provoking speculation that hominins using Yarimburgaz Cave were not necessarily exploiting large animal resources.

In sum, Stiner et al. used multiple lines of evidence to infer that the dominant process of assemblage accumulation and formation at Yarimburgaz involved hibernation deaths over many cohorts of cave bears, with intermittent predation and scavenging on them, as well as considerable bone attrition in place over time. Rodents gnawed bear remains in preference to elements from other species. Carnivores, probably wolves, used the cave occasionally as a shelter, carrying in parts of ungulate carcasses and those of other carnivores. Hominins, perhaps Neandertals, visited the cave and left stone artifacts, but the mammal bones do not testify to their intensive involvement with carcass acquisition.

17.1.5 What Created the Assemblage: Late Pleistocene and Early South American Caves

South America has seen its share of controversies over the meaning of cave deposits with human artifacts and animal bones, beginning with the early finds of now-extinct Pleistocene fauna associated with Paleoindian projectile points in Tierra del Fuego and Patagonia (Bird 1938). These debates only intensified with the advent of radiocarbon dating, which showed these sites to be 10,000–13,000 years old (Borrero and McEwan 1997). Since many of the earliest sites were in caves and rock shelters where carnivores and even giant sloths took refuge from the cold climate of the late Pleistocene and early Holocene in the puna and Patagonia, the same questions of behavioral association as arose with much earlier deposits in Africa and Eurasia emerged.

Zooarchaeological bone surface modification analysis has done much to reduce the ambiguities of some deposits. For example, cut marks have been discerned on the bones of the giant sloth *Mylodon* as well as on those of extinct horses at Fell's Cave and the cave site of Tres Arroyos, Tierra del Fuego (Mengoni Goñalons 1987). The bone-accumulating and crunching effects of a lion-sized jaguar, *Panthera onca mesembrina,* up to 30% larger than modern jaguars, are seen on large mammal bones from several Pleistocene caves that the species evidently used for dens (Martín 2008), including the famous Mílodon Cave, Chile.

However, in cases where caves contain evidence of both carnivores and humans, the problem remains of how to distinguish their respective influences in bone accumulation and modification, as well as how to compare sites. Mondini (2005) took an interesting approach to comparing two early Holocene cave sites in the dry Puna, or Altiplano, immediately east of the Andes. Paralleling the actualistic research of zooarchaeologists in Africa, researchers documented the behavior of living carnivores in their interactions with prey species, both as primary predators and as scavengers, and the outcomes of those interactions in terms of bone refuse accumulations and modifications (e.g. Borrero et al. 2005; Mondini 1995; Mondini and Muñoz 2008). In the drier zones of Holocene South America, the main carnivores are the puma, small cats, fox species of the genus *Pseudalopex,* and two mustelids that occasionally hunt small prey. Mondini notes that the archaeological record of the Puna seems to testify to more intensive human use of caves and rock shelters from the latest Pleistocene to early Holocene. Given its dry climate and relatively low productivity, both early immigrant humans and nonhuman carnivores in the Puna are expected to have existed in relatively low population levels, but caves and shelters would have been zones of spatial overlap in their activities. Today, foxes have become commensal with humans throughout the region, scavenging domestic camelids and caprines. However, Mondini stresses that, during these initial phases of Puna occupation by hunter-gatherers, one must explore, rather than assume, the relationships among humans and carnivores.

Mondini analyzed two excavated archaeofaunas dating to the early Holocene. Inca Cueva—cueva 4 (ICc4), is a cave in a gorge complex in the so-called Dry Puna of Jujuy Province, Argentina, which four radiocarbon dates place in the tenth-to-eleventh millennia BP. Pollen evidence from the deposits reflects a somewhat cooler, wetter climate than today's. Quebrada Seca 3 (QS3) is a rock shelter in a gorge in the Salt Puna of Catamarca Province, Argentina, with radiocarbon dates in the eighth-to-ninth millennia BP. Mondini restudied a QS3 faunal sample from a level dating eighth-to-ninth millennia BP. It is assumed from regional environmental evidence that a drying trend characterized this time span in the Puna.

Given that Puna carnivores differ in size and habits from those documented in the African and Eurasian actualistic literature, Mondini constructed expectations for carnivore-only assemblages from actualistic observations and analysis of five modern Puna carnivore shelter deposits where humans were not involved. She adapted Behrensmeyer's (1991) "taphogram" approach to codify and organize these data and to compare these with ICc4 and QS3. Behrensmeyer's approach calibrated various lines of evidence using a numeric scale of incidence (e.g. 0–25, 0–100) and with

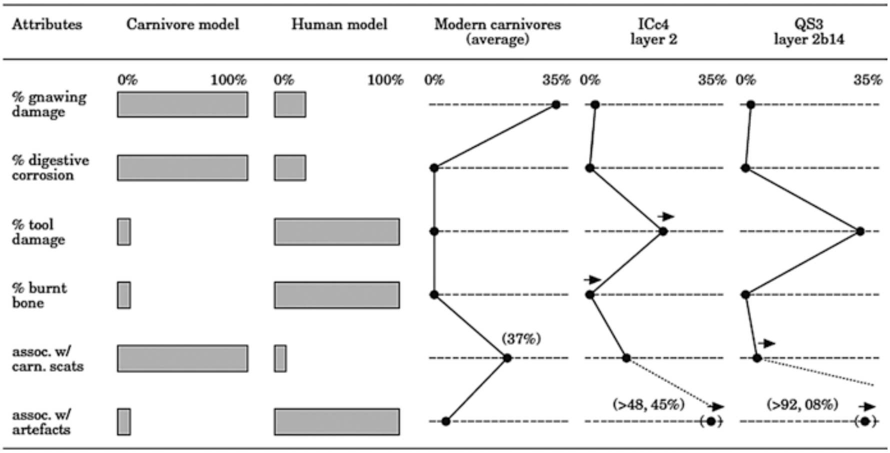

Fig. 17.1 Mondini's (2002:798, Fig. 2) adaptation of the Behrensmeyer "taphogram" approach to fossil deposits, showing average modern Puna carnivore bone deposits compared with ICc4 and QS3 cave and rock shelter archaeofaunas. (Used with permission of the N. M. Mondini and Elsevier)

ordinal rankings (e.g. "unabraded" through "highly abraded"). The multivariate values for a specific assemblage are then plotted along horizontal scales to describe the patterning of evidence in a given fossil assemblage and to compare that pattern with those of other assemblages.

Mondini used this method to make a simple, multivariate visual comparison of the average carnivore cave pattern versus those displayed by ICc4 and QS3 (Fig. 17.1). Clearly, the ancient assemblages differ from the average of carnivore assemblages. She then explored whether some of this difference could be attributed to post-discard, bone mineral density mediated attrition, as one might expect in archaeological deposits. Using Spearman's rank-order correlation coefficient, she determined that the frequencies of camelid bones in both archaeofaunas do not correlate significantly with their durabilities, a topic to be discussed in detail in Chap. 21. One of the most impressive outcomes of the analysis is how low the incidence of carnivore gnawing was in both the ICc4 and QS3 assemblages, especially given the scavenging of human trash she documented for modern carnivores in the Puna. Camelid bones in modern carnivore dens are heavily gnawed. From this, Mondini concluded that, while carnivores might have had a minor role in forming the archaeological deposits, "their incidence has not significantly affected the zooarchaeological record in terms of integrity – neither through modification and attrition, nor through addition" (Mondini 2005:799).

Finally, Mondini uses the two early Holocene deposits to comment on the possibility that these reflect a span during which local nonhuman carnivores were as yet adjusting to the entry of humans into their predator guild of the Puna. She suggests that, over the time since then, foxes especially have become more adept commensals, exploiting human habitations for their own benefit. While this speculation needs to be assessed with further archaeofaunal evidence associated with the Holocene, it provides an interesting contrast with Africa, from where so much actualistic information has been derived – and often generalized as "universal" – but where hyenas, canids, and humans had been coevolving over several millions of years.

17.2 Methods: Taking Effects of Prior Probabilities into Account

In the cases presented in this chapter, researchers have employed a number of statistical approaches to determine differences between and among samples in their own research. These investigations have compared diagnostic diaphysis breakage patterns, as did Marean et al. (2000, see also Fig. 11.9), assessed patterns of spatial association of bone modifications, taxa, and artifacts, as did Stiner et al., and checked how well bone durability predicted the frequencies of different skeletal elements and, by extension, how likely was post-discard attrition, as Mondini did. In each case, the use of statistical tests was straightforward, aimed at comparing datasets – either actualistic to archaeofaunal or among archaeofaunal samples.

None of these approaches used statistical analysis to characterize and compare assemblages as a whole. Behrensmeyer's 1991 taphogram approach took a step in that direction by employing a graphical method to describe paleontological assemblages using units of comparison with quantitative bases. This approach was also employed by Stiner (1992) with ordinal scale variables, such as abundances of various classes of prey, in a discussion that considered the effects of scales of time averaging on different faunal samples. More numerate readers may have realized that taphograms presented here could readily be converted into multivariate statistical analyses, although the analytic categories differ, some being interval and others ordinal (Chap. 18).

Not long after the taphogram approach was published in *Taphonomy: Releasing the Data Locked in the Fossil Record* (Allison and Briggs 1991), researchers in paleoecology and paleobiology began to engage in such multivariate statistical assemblage characterization studies. Behrensmeyer et al. (2000) summarized some earlier approaches in this area. Paleontological taphonomists take into account the critical question of how much time, and how much differential attrition based on size- and body part-durability that a fossil deposit encompasses ("time-averaging"). Zooarchaeologists, especially paleoanthropological researchers, may benefit from exploring paleontological assessments of the relationships among time scales in varied paleontological deposits, the "fidelity" of such deposits to the ecosystems from which they were derived, and, as a result, the appropriately scaled paleobiological research questions to ask. Their approaches include actualistically based, "forward modeling" of outcomes, with stipulated processes and ranges of outcomes.

Zooarchaeologists might also profitably explore the application of Bayesian statistical approaches to characterizing and comparing multi-agent accumulations. This approach was raised as an approach to the variability intrinsic to age estimation based upon developmental markers. Archaeologists are probably familiar with the application of Bayesian statistics to estimating the most likely age range from multiple radiocarbon dates. It is a widely used method in ecological studies, where it is deemed better able to assess outcomes of statistically operating causal processes in ecosystems (see Chap. 3). As noted in Chap. 7, Bayesian statistics differs from the probabilist statistics more familiar to most of us in its base assumptions and in its incorporation of "prior probabilities" of specific outcomes. Many variables studied by multi-agent accumulation analysts are statistically linked to an actor or a causal process. For example, the notches made by carnivores' static loading on diaphyses fall within a specific range of dimensions, while those produced by hominins' dynamic, hammerstone-aided loading fall in another, with an area of overlap (Chap. 12). This renders the inference of agency solely on the basis of notch size less than totally assured; however, some size ranges of notches are more or less likely to be linked to carnivore teeth versus hammerstones. Such "prior probabilities" of an identified causal effector can be assigned, and, taken together with other, actualistically derived probabilities, can point to the likelihood of specific actors being involved.

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Chapter 18
Reasoning with Zooarchaeological Counting Units and Statistics

The very idea of statistics plunges a substantial proportion of archaeology students either into a semi-comatose state or outright panic. I have been one of those students, for whom only repeated exposure to the subject has diminished the strength and duration of these reactions. But, just as one cannot discuss patterning in faunal assemblages without counting, one cannot adequately assess hunches about similarities or differences between and among archaeofaunas without employing statistically based comparisons. This chapter provides an overview of commonly used statistical tests in zooarchaeology. It starts with basics because, though thoroughly convinced of the value of the topics to be covered, basics are where I usually begin. Hopefully, this approach is useful to some readers, and math whiz readers are asked to literally overlook this back-to-basics approach. Chapter 18 opens by outlining what statistical tests ultimately tell us. It then discusses the statistical tests appropriate to the various zooarchaeological counting units of measure. It then outlines the respective strengths and weaknesses of zooarchaeological counting units, reporting on recent debates over which are the best measures of relative taxonomic and skeletal element abundances. It ends with a discussion of zooarchaeological counting units and statistics as tools that are variously useful or appropriate to different research problems. The reader might wish to review Chap. 10's section on NISP, MNI, MNE, and MAU, as these were introduced there.

18.1 Commonly Used Statistical Tests in Zooarchaeology

When comparing two or more things, one asks whether they are similar or different. Sometimes this may be straightforward to answer, as when the question is, are these five apples green, or are all of these stones human artifacts? As questions become more specific, such as, are all the apples the same shade of green, or are these artifacts projectile points, how to answer the questions becomes more complex. It may often involve units of measure, as with a color's hue and chroma characterized by

D. Gifford-Gonzalez, *An Introduction to Zooarchaeology*,
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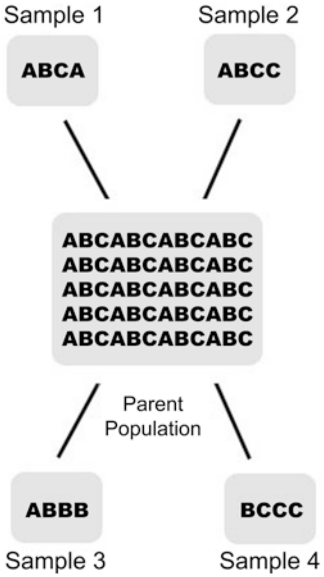

Fig. 18.1 A hypothetical parent population and four samples drawn randomly from it, showing the possibility that the samples may be differently representative of the parent population (Illustration by the author)

the Munsell® color system. In the case of the artifacts, measurements of length, width, and details of overall shape, as in stem length or angles of notching, if any, may be used to answer the question. With such artifacts, other questions may arise: is the weight of the individual artifacts within some rather narrow range of variation? Does there seem to be a preference for a relatively rare raw material for making the points? To answer these questions, we need is a set of standards to assist our judgments about similarity or difference.

18.1.1 Populations, Normal Distributions, and Samples

Probabilistic statistical tests evaluate such questions by calculating the likelihood that the specimens we are studying could have derived from the same *parent population*. Figure 18.1 shows a hypothetical parent population and four samples randomly drawn from it. Samples 1 and 2 have are quite similar to the parent population and to each other. They are therefore highly likely to have been drawn from the same parent population. By contrast, Samples 3 and 4 differ substantially from each other, and they might not be drawn from the same parent population, although it is possible. This sliding scale of likelihood underlies probability-based comparisons of samples.

In nearly all cases, statistical tests do not have a "real" parent population against which to compare samples. Instead, statistical inference assesses the *probability* of a parent population producing a sample. When two samples are compared, the test assesses the likelihood that the respective samples could have been drawn randomly from the same population of values. The *p*-value, is an estimate of the likelihood

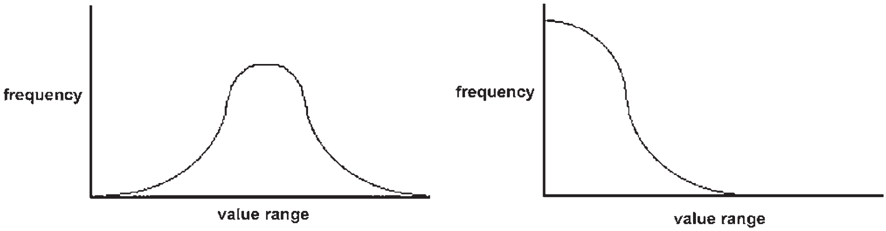

Fig. 18.2 **Left:** a normal curve, showing symmetrical distribution of values around a mode. **Right:** a Poisson distribution, showing a fall-off in values in one direction from the mode only (Illustration by the author)

that the first value is drawn from the same parent population as the second. Such *p*-values expressed as a decimal fraction of 1.0, such as: 0.50 0.05, 0.01, 0.001, and 0.0001 etc. A *p*-value of 0.70 indicates they are quite likely (70%) to have been drawn from the sample hypothetical parent population, whereas 0.001 indicates a much lower (1%) likelihood. A *p*-value of 0.05 value is usually considered to be on the cusp of statistical significance, but it involves some probability (5%) that the compared sets are drawn from the same population. Results of $p = 0.01$ are considered "significant," and $p = 0.001$ levels are termed "highly significant." Values >0.05 are not considered statistically significant, although many cases from biology and ecology show that strong, biologically relevant *trends* or tendencies are not always statistically significant.

Most statistical tests' derivation of *p*-values assume that a trait's values are randomly distributed in a *normal distribution* around a mode. This would be the case, say, with the tail length in a species of squirrel, where some are shorter, some longer, but most fall around a *mode*, or central tendency, where most data points lie (Fig. 18.2, left). Normal curves are symmetrical, having their highest point at the mean of the variable values, that is, the mode and mean values coincide, and terminate in zero frequency of occurrence of the variable of interest – in this case, lizard tail length – at either end of their distribution. This is called a two-tailed distribution – which is unrelated to squirrel tails, but rather to the tapering ends of the values.

However, some traits in nature, such as DNA mutation rates, and in archaeology, such as the sizes of flakes driven from a single core by percussion flaking, are not distributed in a normal curve, but rather in what amounts to half of a normal curve, with the mode falling off in only one direction of values. This is called a one-tailed or Poisson distribution (Fig. 18.2, right), which can have the mode to the left or the right. Common estimates of likelihood are based on the assumption of a normal curve one-tailed or two-tailed curve. However, not all data distributions follow "normal curve" models; some can be bimodal or show no mode, and tests assuming a normal distribution become less reliable when applied to these.

Not all statistical tests can be used with all types of variables. Understanding the differences among commonly used types of variables is important, especially because some common zooarchaeological quantification units incorporate basic assumptions that in effect disqualify them from certain statistical tests. The next section provides definitions of terms and tests commonly employed in zooarchaeological statistics. It then discusses those specific aspects of zooarchaeological counting units – NISP, MNE, MNI, MAU – that limit the types of tests that can be used. This does not mean these zooarchaeological measures are "defective," but rather that effectively using them requires some circumspection.

18.1.2 Discrete vs. Continuous Variables

Variables are basic units of counting that describe attributes of what we want to study. Variables could include coat color, height, depth, number of cut marks, and so forth. A given variable differs in its *values*. Coat color in cats, for example, may be black, white, orange, gray, brown, etc. Adult humans can have a wide range of heights. Lakes vary considerably in maximum depth and volumes of water. In using variables to compare two or more samples, it is necessary to understand how the variable "behaves" in terms of those values.

Two general types of variable may be distinguished: *discrete* and *continuous*. The numbers on the sides of playing dice are an example of a discrete variable. When someone throws dice, he or she can only come up with one of six values on each die. One never throws a $2^{1/2}$ or 5.67. Another example is DNA certain codons producing the expressed blood types of the ABO blood group: one is A, B, AB, or O. Discrete variables can be either finite (a definably limited number of values, such as the examples given above) or countably infinite, a more abstract possibility that does not concern archaeofaunal analysis. Thomas (1986) gave the example of a book of an infinite number of pages, but in which each page would nonetheless be a discrete, predictable member of a counted series, as in pages 101, 102, 103, etc.

Such discrete variables contrast with, for example the range of numerical possibilities in heat as measured by a thermometer. A Fahrenheit thermometer used to measure body temperature, could display a reading of 98.6° F, but also read 98.2°, 97.8°, 102.4°, and so on. If the thermometer had finer calibrations, gradations between temperature values could be even more precise. Temperature is thus a *continuous* variable. In the abstract, continuous variables can assume an infinite range of values. Common continuous variables include distance or miles per hour, since these could conceivably assume any value, though some may be more common than others.

18.1.3 Types of Variable Scales

Variables can be classified according to the *scales* of the categories, that is, whether and how continuous and discrete values are defined. These are:

1. **Nominal scale**: named categories for entities, such as left, right, red, yellow, *Homo sapiens*, *Bos taurus*, etc., are nominal scale variables. These require only

that the classificatory categories be *exhaustive and mutually exclusive*, that is, red can never be yellow, a human can never be a cow, etc.
2. **Ordinal scale**: "ordinal" implies a ranking, or ordering. This type of variable involves an ordering of discrete categories into *a meaningful sequence of classes ranked along a continuum*. However, the distance between two or more such categories is either unknown or undefined. For example, one can say A > B > C, but not stipulate by how much, or even whether, the interval between each variable is of the same magnitude. By the same token, "sedentary" is less mobile than "transhumant" to an unspecified degree, species A is less arboreal than species B, etc.
3. **Interval scale:** variables of this type possess all the properties of ordinal scale variables except that they also possess equal distances (*intervals*) between each variable category. Thermometers and calendars are interval scale. Interval scale devices do not necessarily begin their calibration at zero. For example, thermometers, which have zero as a value, have an interval scale that goes below zero. Because the intervals are stipulated in a quantifiable way, these scales *can be mathematically manipulated through addition and subtraction*.
4. **Ratio scale:** these variables are based on scales in which *the starting point is fixed* rather than arbitrarily defined. Such scales quantitatively express the relationship between physical properties, such as miles traveled per hour, number of inhabitants per hectare, number of beta particle emissions per 24-hour period, etc. In all cases, *zero is a fixed point in relation to the scale established*, whereas in the interval scales, only the space between points need be specified.

The distinctions outlined above are significant because certain statistical tests can only be applied in certain variable scales and not to others. Choosing the statistical test appropriate to the variables used in zooarchaeology depends on understanding the nature of its basic counting units and other associated values, such as nutritional indices and bone-mineral density indices, commonly used in the field.

18.1.4 Parametric and Nonparametric Statistics

Parametric variables fulfill certain statistical criteria, and tests applied to them assume that these criteria are met. Paraphrasing and reducing Siegel and Castellan (1988), parametric variables require the following:

1. Observations must be *independent*. That is, selection of any one case from a population in a sample must not bias the chances of any other case being selected.
2. The observations must have been randomly drawn from a *normally distributed population* (Fig. 18.2), with predictable implications for computation of their means.
3. Populations to be compared must have either the *same variance* or a known *ratio of variances*
4. Variables must be measured at *least in an interval scale*, so that normal arithmetic operations can be performed.

Tests that operate on these assumptions include comparisons of means and the variation around them. Some, such as the Student's t-test, allow greater leeway on these conditions; because the distributions need only be approximately normal, variables could exhibit largely independent errors, etc. However, even Student's t-test requires that the variables be ratio or interval scale (Siegel and Castellan 1988). As should be clear from examples given above, many variables of interest to archaeologists may not satisfy all or any of these requirements. Therefore, other ways of assessing whether two samples are similar or different are needed.

Nonparametric statistics are designed to be used in cases where not all the parameters of the variables of interest listed above are fully known, such as whether a variable has a normal distribution and if a standard deviation of the mean can be calculated. These tests can be used under *any one* of the following conditions:

The variables may be nominal, ordinal, and interval scale.

or

The variables are *not distributed randomly* but in a distributional pattern that is unspecified, i.e., not necessarily a normal distribution.

Since many variables studied by archaeologists, and specifically zooarchaeologists, have an unknown distribution, this last aspect of nonparametric statistics is especially important. Nonparametric statistical tests appropriate to each type of variable scale are summarized below.

1. Nominal scale variables may be subject to parametric statistical tests, such as the Chi-Square test or Fisher's Exact test, but analytic tactics such as regression analysis are not appropriate
2. Ordinal scale variables may be subject to the tests listed above for nominal scale variables and also to rank-order correlation coefficients, such as Wilcoxen Two-sample test, Kendall's tau, Spearman's rho, and the Kolmogorov-Smirnov test. Kendall's tau and Spearman's rho are often used in assessing the degree to which relative nutritional utility or bone mineral density indices predict element frequencies in an assemblage. The Kolmogorov-Smirnov test compares cumulative frequencies commonly run on ordered percentages, such as is the case with mortality profiles and survivorship curves. As with nominal-scale variables, regression analysis is not appropriate.
3. For interval scale variables, rank-order correlation coefficient tests, such as Kendall's tau and Spearman's rho, are appropriate, as are linear regression and correlation.
4. Ratio scale variables are amenable to all mathematical operations and thus to all parametric tests.

18.1.5 Correlation Coefficient Analysis

The correlation coefficient, r, expresses how two interval or ratio scale variables, x and y, are related to one another (co-related). Variables are often displayed on a bivariate plot (Fig. 18.3a–c), as are similar variables in regression analysis, but

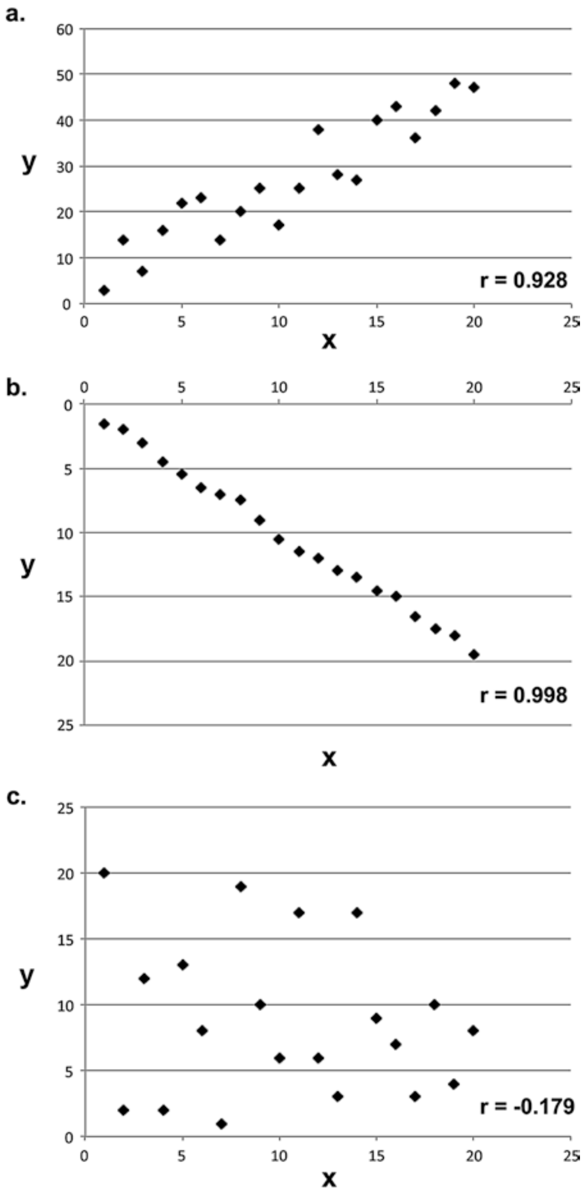

Fig. 18.3 Three cases in which the value of x relates to the value of y: **a.** a strong *positive* correlation exists between the values of x and y; **b**. a strong *negative* correlation, where increasing values in x correlate with decreasing values in y; **c**. a case in which no consistent relation exists between the two variables. Pearson's r values provided in each example. (Illustration by the author)

several key differences between these two approaches exist. First, correlation coefficients do not assume a causal relation between the two variables, as would regression analysis. In correlation coefficient analysis, x and y variables are theoretically interchangeable, whereas, for the purposes of regression analysis, values of x is assumed to determine values of y (see below). Second, correlation coefficient analysis does not assume that the variables have a normal distribution, whereas assumption of a normal (Gaussian) distribution is basic to regression analysis. Third, only regression analysis "fits a line" to an x-y variable distribution (see below).

Correlation coefficients can range from 1.0, reflecting perfect positive correlation, to 0.0, reflecting no correlation between the two variables examined. Correlations can be positive, with both values increasing together in a positive direction (e.g. Fig. 18.3a), or negative, with one value decreasing as the other increases (Fig. 18.3b). A negative correlation such as that shown in Fig. 18.3b always involves one positive variable; if both variables moved in a numerically negative direction, this would produce a positive correlation. It is worth reiterating that correlation does not equal causation.

18.1.6 Regression (Coefficient of Determination) Analysis

Regression analysis explores whether, given multiple cases, a given variable, x, determines the value of a second variable, y. For the purposes of exploration, x is assumed to be the *independent (determining) variable* while y is the *dependent (or determined) variable*. Regression analysis can explore simple linear patterns of relationship, such as those shown for total body weight vs. skeletal weight by Reitz and Wing (2008:64–70), or relationships in which the variables covary in a more curvilinear relationship, such as crown heights of molars as they wear over time (Chap. 4). More complex forms of regression analysis use multiple variables simultaneously. Regression analysis requires that both variables be interval or ratio scale variables. One cannot regress ordinal or nominal scale data; nonparametric statistical tests work for those scales.

Regression analysis has been used in zooarchaeology on variables as bone size in relation body length, practices largely drawn from established in wildlife management research (cf. Reitz and Wing 2008:186–187). In relationships such as that of bone size and body length, zooarchaeologists use regression coefficients of determination, derived from contemporary measurements of both variables, to estimate the value of one from value of the other when they estimate body length from an animal's bone length.

The example in Fig. 18.4 suggests that the variables involve a causal relation, but regression analysis itself does not *prove* causation. Zooarchaeologists as well as other scientists who use regression analysis may have a high coefficient of determination, but they still must investigate *how* these variables relate in functional terms, and the underlying causes of their relationship. For example, in 18.4, in this relationship, the number of cats is the determinative variable and volume of cat poop is the determined variable, however, despite our intuitive grasp of the functional relationships involved in this simplistic example, a scientific approach would ask that these be specified by direct observation, to confidently proceed assuming that the former has a causal relation to the latter.

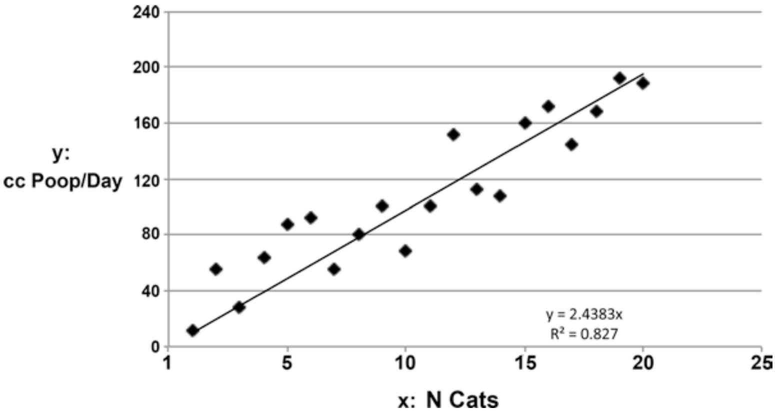

Fig. 18.4 A plot showing a distribution of variables with regression line, with formula for the intercept and R^2 (Illustration by the author)

18.1.7 Simple Linear Regression

In simple linear regression, a scatter of individual points of x/y values plotted, which is readily done with many computer applications, including Excel® and other database applications. Often, simply visually inspecting a plot will indicate whether a strong relationship exists between these variables; this can be expressed quantitatively as r, the correlation coefficient. Next, to specify how well (precisely) x predicts y, one multiplies r by itself, resulting in r^2. If there is a perfect correlation r = 1.0, then r^2 will also be 1.0. However, many strong r statistics are more like r = 0.8, in which case, r^2 is 0.64, meaning that 64% of the variability of y, the determined variable, is explained by the regression model. The r^2 is also called the *coefficient of determination*: the higher the r^2, the more of the variation in the data is accounted for by the regression line. Recall that 1.0 would represent perfect determination, so how good is the r^2 of 0.64? This is done by assessing the probability that the results were not associated with the action of x in the regression model. The *p*-value is calculated assuming a normal curve. The lower the *p*-value, the more likely the action of x on y is the cause of the patterning.

Another way of visualizing how well x accounts for the variation in y is to present the data with two lines running parallel to the regression line, showing the 0.05 confidence levels of estimates predicted by the regression line, that is, two *standard errors* on either side of the average in a two-tailed normal distribution. The same estimate error range can be shown for individual points, each with their own standard errors of their mean (e.g. Fig. 18.5). The standard error quantifies the *precision* of the mean, or average, value in a sample. This is in turn derived from th*e standard deviation*, the degree to which individual values in a sample differ from the sample mean. The standard deviation ("± value") is the sum of the squares of the difference between each value in the sample and the sample mean, divided by the total number

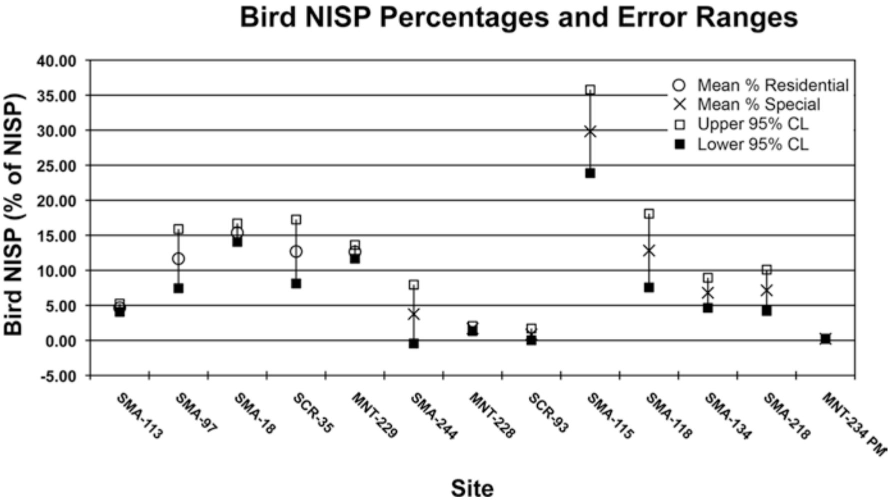

Fig. 18.5 A plot showing the 0.05 confidence levels (2 standard errors) of mean bird NISP frequencies at 13 archaeological sites in southern San Mateo, Santa Cruz, and northern Monterey counties. Longer-term residential sites are marked with an open circle, while short-term residential and special purpose sites means are marked with an X (From Gifford-Gonzalez et al. 2013:307, Fig. 2, produced by R. Cuthrell, used with permission of Taylor and Francis and Society for California Archaeology)

of sample values minus 1, with the square root taken of the resulting number. A cogent discussion of "why N-1?" can be found in Motulsky (1995-2015).

Again assuming that the parent population follows a normal distribution, one standard error accounts for about 67% the variation around a mean, while the two standard error space accounts for about 95% of the variation around a mean. Graphically, the more space between the regression line and the 0.05 confidence lines, the more highly variable the values in the sample are.

18.1.8 Spearman's Rho and Kendall's Tau, Nonparametric Correlation Coefficients

Chapters 20 and 21 outline how, during the 1990s, zooarchaeologists debated whether nutritionally motivated human selectivity or bone durability has more influence on creating the structure of certain archaeofaunal samples. Zooarchaeologists Grayson and Lyman recognized that both nutritional value indices (e.g. MGUI) and bone mineral density indices were ordinal scale variables, in which each index value was a ratio, but that the distance between any two skeletal elements' values was not the even interval required by parametric statistics such as regression analysis. They therefore advocated using one of two nonparametric tests of the correlation of element frequencies against these indices, Spearman's rho (or R) and Kendall's tau (or T), rather than regression, which requires ratio scale variables. Both Spearman's rho and Kendall's tau basically assess how well x (in this case the index being studied) predicts the frequencies of the osteological elements, up to now usually expressed as %MAU or %NISP.

Statisticians consider that Kendall's tau and Spearman's rho have similar basic assumptions and statistical power (Siegel and Castellan 1988). Yet Kendall's tau has a very different computational formula than Spearman's rho because it expresses *probabilities*, rather than the *amount of variability explained*, as does Spearman's rho. The Kendall's tau product represents the difference between the probability that the two compared variables are in the same order and the probability that they are in a different order. Spearman's rho computes its outcome much like the simplest regression correlation coefficient, the Pearson product moment correlation coefficient: its outcome expresses the proportion of variability accounted for by the correlation. However, Spearman's rho is computed from ranks rather than interval or ratio scale variables (StatSoft 2013). Spearman's rho assumes that the variables assessed are at least ordinal scale, so individual observations can be ranked into two ordered series. For example, in any assemblage, one can list element frequencies in a rank from highest to lowest NISP. Likewise, bone mineral density (BMD) per cubic cm for various elements can be arranged from the highest BMD values to the lowest.

18.1.9 The Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test is a nonparametric test that compares the cumulative distributions of two datasets to assess whether they differ significantly. The Kolmogorov-Smirnov test makes no assumption regarding the normal distribution of the data but depends on a continuous distribution of the variable graphed Siegel and Castellan 1988). Classically, it is used to compare a curve of unknown distribution of the parent population against a cumulative curve produced by a normal distribution. However, it can also be used to compare two sample curves. Technically, it is a goodness-of-fit test between two curves. It produces a D-statistic that expresses the degree of discrepancy between the two distributions and hence whether the hypothesis that the two curves are similar – or, that the "observed" of the one matches the "expected" of the other – is supported. In zooarchaeology and other areas of archaeology, this test has normally been applied to cumulative percentage frequencies of values of a variable (Siegel and Castellan 1988). The Kolmogorov-Smirnov test has been used by Klein to compare mortality profiles, which plots cumulative frequencies of ages at death, or mortality profiles (Chap. 22).

The balance of this chapter explores some of the confounding effects of using NISP, MNI and other derived measures as the basic variables of comparison in zooarchaeology.

18.2 Problems with NISP, MNI, MNE, and MAU

Whether they are interested in shifts in species abundances with climate change over time, or in comparing the relative frequencies of long bones to axial elements from two sites, zooarchaeologists are dealing with measures of relative abundances. Even before deciding on appropriate tests for assessing similarity and difference between or among samples, a researcher must choose the counting unit to be used to make the comparisons. The fundamental question for someone working with archaeofaunas is whether one's choice in counting unit affects the patterning perceptible in quantitative data. This section will draw upon Grayson's (1984) classic assessment of these issues, in his book, *Quantitative zooarchaeology*, as well as Lyman's (2008) *Quantitative paleozoology*, and other discussions of statistical methods in zooarchaeology e.g. (Marshall and Pilgram 1993; Morin et al. 2017a; Ringrose 1993; Pilgram and Marshall 1995), including experimental research on the performance of various counting units under controlled circumstances where taxonomic and skeletal element "input" was known (Morin et al. 2017a).

Grayson has a long history of research archaeofaunas of the western United States and has written extensively on quantification of faunal data (Grayson 1978, 1979, 1981). Much of Grayson's earlier research focused on the paleobiogeography and diachronic changes in relative abundances of taxa in the Great Basin of western North America, using NISP or percentages of NISP of different species. *Quantitative zooarchaeology* (Grayson 1984) focused on the relationship between analytical methods and perceived patterning in archaeofaunal data. By experimentally manipulating data from his own and others' analyses, Grayson explored the possible effects of sample size and choices in archaeofaunal sample subdivision in relation to the quantitative units chosen on species abundance data, arguing that some "patterning" could simply be produced by analytic choices in combination with specific quantitative measures.

18.2.1 Problems with NISP

NISP is the most basic statistic in zooarchaeology. It is "primary data" in the sense that it is the total of identifiable (and, as used by some researchers, less identifiable) specimens that can be counted. As a raw count, NISP appears to behave as a continuous, interval scale variable, with increments of one between each value. Moreover, NISP is "set" to begin at zero, so it has at least one property of a ratio scale variable. It appears therefore to be potentially amenable to parametric statistics.

However, when NISP is used to estimate the proportional representation of various taxa in an archaeofauna, several biologically intrinsic properties and postmortem taphonomic processes can bias relative taxonomic proportions. These include:

1. The variable numbers of skeletal elements in bodies of different taxa.

2. Human taphonomic factors, including
    (a) differential effects of butchery and transport on bodies of different-sized taxa and
    (b) differential intensities of breakage on skeletal elements of taxa with different within-bone nutrient levels.
3. Non-human taphonomic biases in taxonomic representation through differential destruction among elements with different durability.
4. Collection biases (screen size, visual inspection, etc.).

Moreover, Grayson (1984) notes that we can normally assume that it is highly likely that more than one skeletal element of a given taxon in an archaeofauna actually derives from the same individual, and therefore NISP cannot guarantee the *specimen independence* required by nearly all the statistical tests. Given this, some have opted to use MNI to correct for these problems. To these general problems, one should add a consideration of the Morin et al. (2017a, b) assessment of NISP's performance as an estimator in an experimentally controlled situation (see Sect. 18.3).

18.2.2 Problems with MNI

Because it depends on the most numerous unique element of a given taxon, MNI would seem to resolve the problems created by specimen interdependence, differing numbers of bones in various vertebrates' bodies, differential recovery methods, and some differential transport and processing. While MNI may help offset the effects of modest differences in transport and processing of different taxa, but this has logical limits. For example, MNI cannot "correct" for the absence of elements that were reduced into small, unidentifiable scrap through processing, nor can it testify to the presence of flesh from animals, such as flensed whales, whose bones were never transported to a site.

Despite MNI's efficacy at coping with some problems inherent to NISP, Chap. 10 foreshadowed problems with MNI that affect it as a measure of relative element and taxonomic abundance, and thus as an effective means of comparing samples within or among sites. These can be divided into four areas:

1. Effects of different sample aggregation strategies on MNI.
2. Faulty assumptions of specimen independence for MNI in stratified sites.
3. Effects of differences in sample size (expressed as NISP) on MNI.
4. Problematic assumptions about MNI in relation to carcass utilization.

The next sections discuss each of these in turn.

18.2.2.1 Effects of Aggregation Strategies on MNI

Grayson (1984) demonstrated that MNI is sensitive to the relative fineness with which a site is subdivided, or "aggregation effects." Aggregation refers to the strategy of grouping specimens in a site's archaeofauna into sub-assemblages, based on various criteria. For stratified sites, this commonly involves aggregating the archaeofauna into stratigraphic samples according to matrix lithology or artifactually distinctive strata. An example is Klein's (1978, 1979, 1981) aggregation of small lithologic unit samples from Elands Bay Cave and Klasies River Mouth Cave 1, South Africa, into larger Middle Stone Age aggregates, based on the overall stone-working traditions associated with those strata. This allowed Klein to compare age structures in these faunal samples with those of similarly aggregated Later Stone Age samples from these and other South African sites. Another common aggregation practice in archaeology is treating house-floor or house-compound assemblages from a site as subunits and comparing trash-pit samples independently, as did Crader (1984, 1989) for Thomas Jefferson's main residence and slave quarters at Monticello, Virginia.

These practices are often logical from an archaeological viewpoint, but they can produce unintended zooarchaeological consequences, by inflating MNI estimates for various taxa in an unpredictable manner. Figure 18.6 shows data originally presented by Grayson (1984:31) in a different format, illustrating a hypothetical example in which more finely subdividing an assemblage produces higher total MNI figures for the site. This results because the most abundant (i.e. MNI-diagnosing) elements of each taxon are *not evenly distributed* through the entire stratigraphic section. Rather, they are distributed in highs and lows that manifest as varying MNI estimates for different layers into which a stratigraphic section – and the associated archaeofauna – has been subdivided. The high and lows of horse specimen abundances do not track identically with those of cattle because the entry of one taxon into a human campsite or settlement normally doesn't depend on the presence of another taxon. We might even expect independence in the spatial distributions of two taxa to be the case, as with a wild mammal species versus a domestic one. Subdivision of a stratigraphic section can thus produce differing effects on MNI of one taxon in relation to another. This example shows that the patterning perceived in the MNI data, and in the relative abundances of the two taxa, may depend not on some "real" variations in relative abundances, but rather on the units into which a stratigraphic section is subdivided – or aggregated. It follows that the story a zooarchaeologist could tell from these relative abundance data could differ as well.

Especially with stratified sites, whether patterning in archaeofaunal data is just an artifact of how the site was subdivided is of special concern. Archaeologists aim to excavate in rather small stratigraphic slices to maintain maximum control over specimen provenience and, they hope, maximum temporal resolution. In the United States, it has been common practice to excavate in arbitrary 10 cm levels rather than according to sedimentological units, while in continental Europe, very small sedimentological deposits are often dug as discrete units, but some are later aggregated according to their artifactual contents or other criteria. In either case, dividing or

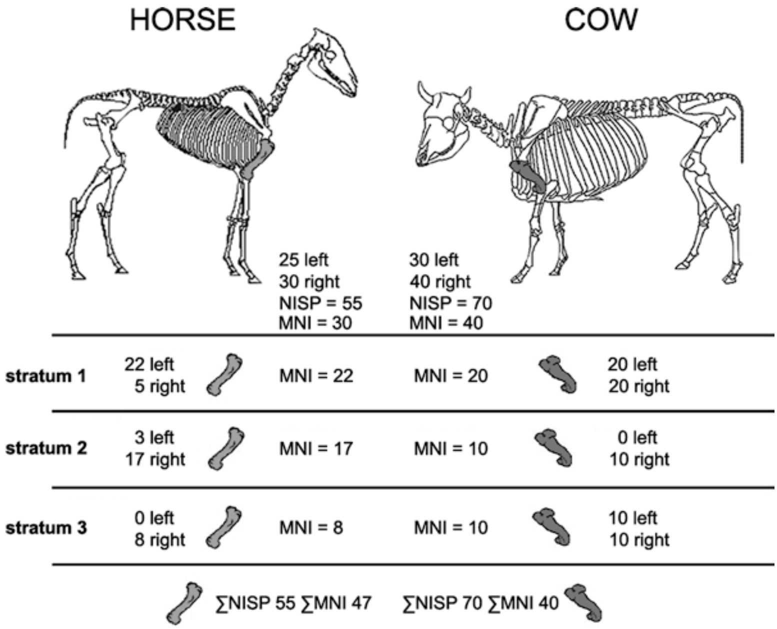

Fig. 18.6 Hypothetical case in which differing aggregation effects emerge through stratigraphic subdivision of a sample. NISP and MNI at the top are based on treating the entire sample as a single aggregate. The subdivided sample produces different total MNI for one of the two species (horse), and therefore a different relative proportion of horse to cattle, compared to the undivided one. (Illustration by author, using data from Grayson 1984:31, Table 2.2)

lumping levels and archaeofaunal samples as opposed to keeping them distinct can impact derived MNI estimates. Criteria for choosing how to subdivide a stratified site may have little to do with the archaeofaunal remains themselves, but zooarchaeologists must be aware that these decisions ultimately can have a major influence on MNI. Not only does this problem affect MNI as a relative abundance statistic, but it also affects other measures of abundance such as Minimum Number of Elements (MNE) and Minimum Animal Units (MAU). Moreover, Grayson (1984:45–48) notes that aggregation effects will impact estimates of other qualities of a sample, such as percent survival of various elements, if these are based on ratios of MNI values.

Hope exists for revealing and resolving this problem in a given dataset. Grayson proposes two strategies for deciding whether the vertical distribution of faunal remains in a site is susceptible to such aggregation effects. The first involves monitoring the distribution of most abundant elements (MAE) for all taxa across the finest possible subdivisions of the stratigraphic section (Grayson 1984:33). If MAE distributions vary from level to level, then aggregation effects are likely to skew relative abundance data. Another approach is to calculate MNI for taxa first in the site sample as a whole, then for major stratigraphic units, and finally for the finest stratigraphic subdivisions possible (Grayson 1984:34). If MNI values vary from one aggregation scheme to the next, then aggregation effects are a potential problem in "reading" the MNI statistics.

Grayson notes that the same problems apply to using MNI in intrasite comparisons of single-component sites, if faunal remains from various features are aggregated in different ways -- for example, treating all trash pits in a site as a single sample vs. comparing Trash Pit A, B, and C. It is therefore critical to assess such intrasite or within-level datasets for the possibility of aggregation effects and to use MNI with utmost caution – or not at all – when aggregation effects appear in the recommended evaluations.

Grayson points out that NISP does not suffer from aggregation effects, and therefore it can be used in situations in which aggregation effects appear to be affecting MNI statistics. He further contends that for subdivided stratified sites, NISP's costs in specimen interdependence are outweighed by its benefits in avoiding aggregation effects. Grayson contends that MNI in stratigraphic sites often does not actually escape specimen interdependence (see 18.2.2.2 *Effects of Specimen Interdependence on MNI in Stratified Sites*).

Recall that Grayson's criticisms apply *only to the use of MNI with sites, and with sampling tactics, in which aggregation effects could operate*. This problem does not affect MNI-based comparisons between sites, if each site is treated as a single sample and specimen interdependence is not a reasonable issue. For example, I might use MNI figures to compare taxonomic abundances of the Prolonged Drift archaeofauna (Gifford et al. 1980) to those of Ngamuriak (Marshall 1990), around 200 km away, since neither sample was subdivided, and it is reasonable to assume specimen independence. Grayson does question the applicability of MNI statistics for intersite comparisons, but they are based on the relation of MNI to sample size (expressed as NISP), to be discussed below.

18.2.2.2 Effects of Specimen Interdependence on MNI in Stratified Sites

MNI seemingly offers an escape from specimen interdependence, but in stratified sites, we have no assurance that the elements of a taxon drawn from one level *necessarily* exclude elements from the same individuals in another level. This is due to site formation and excavation recovery tactics and element distributions across strata.

Strata, even those defined by sedimentary differences, are arbitrary subdivisions imposed by excavators, which may transect elements of one skeleton that do not "map" congruently onto the sediments. Skeletal elements at the top of a thick stratigraphic unit are often spatially closer to elements in the next stratigraphic unit than they are to elements at the lower end of their own stratum. Simply for that reason, they could derive from a single vertebrate individual with skeletal elements in two strata. Even elements recovered from lithologically distinct stratigraphic units, are not *necessarily* from different animals. Processes that form small-scale, sedimento-

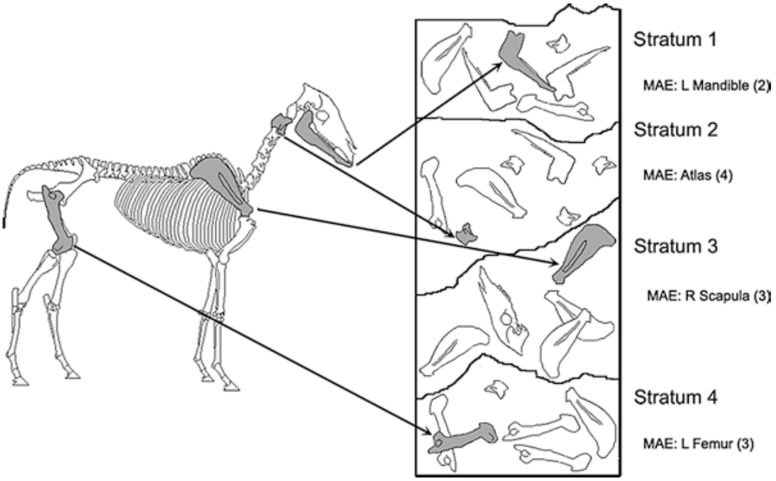

Fig. 18.7 A hypothetical case in which elements of one individual horse (shaded) occur in several strata: a mandible, an axis, a scapula, and a femur. Each of these elements is counted as one of the most abundant elements (MAE) in reckoning the MNI for each layer, thereby introducing specimen interdependence into the MNI statistic (Illustration by the author, inspired by discussion in Grayson 1984)

logically distinct deposits operate independently of human activities, and elements of one carcass theoretically could end up in laterally varied depositional zones – a puddle in a depression, a gravelly high spot – each contemporaneously creating its own depositional matrix.

Moreover, refit studies of bone fragments, ceramics, and lithics show specimens may join together across as much as a meter's depth, transgressing major sedimentological distinct strata lacking rodent or insect disturbance (Villa 1982; Villa and Courtin 1983; Cahen and Moeyersons 1977; Todd and Stanford 1987). This suggests that, like pieces of a broken pot or flakes from a single core, bones of an individual skeleton may appear in more than one stratum.

Because MNI relies on the most abundant element (MAE) in each level, and because different elements may be used to calculate MNI from level to level, a possibility exists that a single animal's skeletal elements could be counted in different levels. Figure 18.7 illustrates a case of specimen interdependence in which the MAE of equids in several strata of a site each incorporate an element derived from one individual.

Summing up, evidence suggests that specimen independence should not be assumed, but rather be demonstrated, for faunal remains in stratified sites. What we know of site formation processes supports Grayson's assertion that, unless one is comparing the same element and side across stratigraphic levels, one should not assume the elements derived from different individuals.

18.2.2.3 Effects of Differences in Sample Size (NISP) on MNI

The preceding sections stipulated that *intersite* comparisons of relative abundance using MNI are not affected by aggregation effects, so long as the respective sites' faunas can be treated as integral samples with no specimen interdependence. Likewise, specimen interdependence problems can be presumed not to affect most sites. However, intersite comparisons using MNI is affected by another factor: the dependence of MNI values at a site on the size of the NISP that generated them. In other words, there is a relation between NISP and MNI that may affect comparisons of substantially different-sized assemblages.

Several researchers, starting with French zooarchaeologist Pierre Ducos (1968), noted that a systematic relationship exists between the size of an archaeofaunal sample (NISP) and the MNI statistic. Ducos compared these data for several early food-producing sites in the Levant and found that the logarithms ($\log_{10}$) of NISP related to the logarithms ($\log_{10}$) of MNI in a consistent, linear fashion. One important finding of Ducos' exploration was that MNI figures tended to overemphasize the abundance of rare (low NISP) species relative to more abundant (high NISP) ones. Ducos' work was essentially replicated by Casteel (1977), a zooarchaeologist, and by Holtzman (1979), a paleontologist, in a related discussion of the likelihood of drawing new unique individuals with increasing sample size.

The situation with rare specimens is as follows: if one has a single element of, say, a rabbit from a site, its MNI is 1. Given the nature of most archaeological bone deposits, it is highly unlikely that drawing a second rabbit specimen will yield a specimen that is not only a rabbit but also the same element and side, thus increasing the MNI to two. Therefore, the relationship of NISP:MNI that started as 1:1 now changed to 2:1, and it's probable that one would have to retrieve many more rabbit specimens from a deposit before finding two elements with which to calculate a new MNI of 2. Let us say that the hundredth specimen was the same as the first, producing NISP of 100 and MNI estimate of 2, or a ratio of 50:1. From this, one can get a sense that very rare elements of one species thus carry relatively more weight when "translated" into MNI than more numerous specimens.

Unlike Casteel, Grayson (1984:53) did not believe that a one-size-fits-all formula for this relationship held, but that the slope and curve must be empirically derived for any specific archaeofaunal sample of NISP $\geq$1000, using the power function $\mathrm{MNI} = a(\mathrm{NISP})^b$, where a and the exponent are derived from the best fit regression line. Grayson further argues that the relationship between NISP and MNI is essentially curvilinear (hyperbolic) in most faunas examined, with the precise shape of the curve varying from site to site, but notes that it can be linear under certain conditions.

The fact that NISP and MNI varies from assemblage to assemblage probably stems in part from carcass processing strategies and in part from the variable number of osteological elements in different taxa (see Lyman 2015). For example, if people regularly killed larger prey animals far from their home camp, they might only bring selected elements back to their base camps. This would lower the ratio of NISP:MNI, because only a small range of elements drawn from whole carcasses would be likely to enter the site and be discarded there, but those that *were* transported would be systematically selected and hence likely to produce higher MNI (Chaps. 19 and 20). By contrast, pastoralists killing their livestock at their home encampment would probably produce higher NISP:MNI ratios because each kill would contribute more elements to a residential faunal assemblage than would hunters' selectively transported body segments (Fig. 15.2).

In sum, statistical tests comparing MNI give equal weight to taxa with NISP:MNI ratios of 1:1 as to those represented by NISP:MNI of 100:1 or even 1000:1. Grayson (1984) advises using MNI with a good deal of caution in such comparisons. No *a priori* method exists for deciding how close ratios must before they are "similar" enough to compare, nor how far away their values must be before they are "different." Is 50:1 different enough from 40:1 that we shouldn't compare MNI with those different ratios? What about 30:1?

Grayson suggests that, because the NISP:MNI problems are compounded with the aggregation effects in stratified sites, one should use NISP instead of MNI for comparing relative abundances. His argument goes as follows: MNI statistics derived from varying-sized NISP are problematic entities for statistical comparisons. Plots of MNI, or of ratios of MNI to NISP against NISP for all sites studied show a consistent relationship between the two variables (Fig. 18.8). Therefore, the information contained in MNI is also inherent to NISP. Since NISP presents none of the size-dependence (nor aggregation effect) problems that MNI does, why not just use NISP? This assertion, and experimental findings on the performance of NISP and other measures will be dealt with in 18.4 What Do You Want to Do, What Tool Do You Need? later in this chapter.

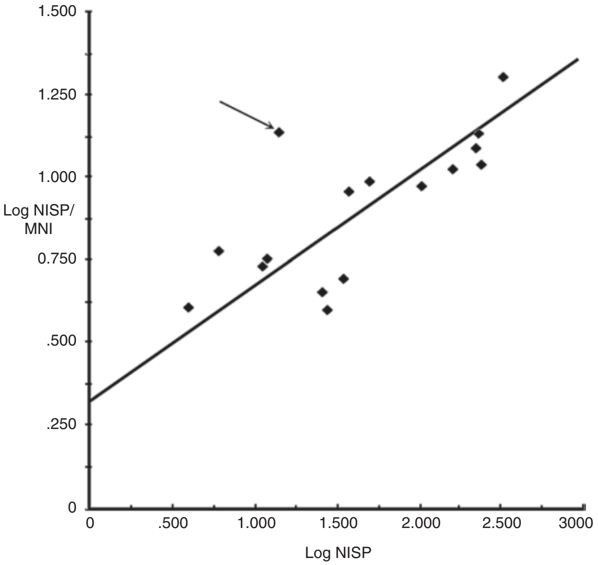

Fig. 18.8 The relationship between MNI and NISP, expressed as $\log_{10}$, for the site of Prolonged Drift. Arrow indicates an outlier in the ratios plotted, a subject further explored in Chap. 22. (Redrawn by the author from Grayson (1984:71, Fig. 2.17), in turn based on data from Gifford et al. 1980)

18.2.2.4 Problematic Assumptions About MNI in Relation to Carcass Utilization

The final problem regarding MNI is of a different order than those outlined above. This has to do with underlying assumptions about the meaning of MNI figures in terms of carcass utilization. Binford (1978) pointed out that researchers have often worked with MNI on the assumption that it represents the minimum number of entire animals once present at a site. Meat weights, for example, are often derived by multiplying the MNI by the average meat yield of an entire carcass of that species. Based in part on his observations of Nunamiut butchery patterns and in part on his preoccupation with possible scavenging strategies in early hominins, Binford questioned this assumption. He contended that the count of elements at a site can, at most, be taken to represent the number of *body segments* present. Lyman (1979) advanced the same criticism of MNI, arguing that the appropriate unit of analysis was not MNI but a “butchery unit” based on the bones actually analyzed and indications of actual carcass subdivision patterns based on butchery marks.

Parallel issues exist with Minimum Number of Elements and Minimum Animal Units as measures of abundance.

18.3 Problems with MAU and MNE

Grayson (1984) criticized the MAU statistic on two counts. First, because it is derived from another unit of counting, the Minimum Number of Elements (MNE), it is liable to estimation problems inherent in the MNE. He concluded that, as a derived estimator of abundance, MAU is sensitive to the same aggregation effects as MNI. Therefore, it should be used with the same caution as MNI in stratified sites and in single-component sites with distinct bone-bearing features. Second, MAU assumes specimen independence from sample to sample, so the same *inter*dependence problems outlined for MNI could also afflict MAU estimates in stratified situations (Grayson 1984). For better or worse (Chap. 10), Binford’s %MAU statistic dominated much of the literature on nutritional utility for a decade, if only because archaeologists wanted to compare their data to those published by Binford. Readers of that literature should consider Grayson's critiques and recommendations for evaluating problematic aspects of these estimates.

In the 1990s and 2000s, many assessments of skeletal element abundances shifted from MAU to MNE (Marean et al. 2001; Marean and Spencer 1991; Domínguez-Rodrigo 1997; Pickering et al. 2008; Pickering et al. 2006). Uses of both MAU and MNE in zooarchaeology generally parallel an increasing concern with prey handling, including butchery, selective transport, culinary processing, and varieties of distribution of body segments (see also Lyman 2008:240–241). This trend supplemented zooarchaeology’s earlier and continued use of NISP and MNI to characterize the taxonomic composition of archaeofaunas, which enabled analyses of environmental change, prey species choice, and, by extension, discussions of different hominin species’ predatory capabilities.

Despite this trend, two sets of scholars questioned whether MNE is essential to assessing element frequencies. Grayson and Frey (2004) and Lyman (2008:214–249), engaged in extended, statistically buttressed discussions of whether the MNE statistic is in fact preferable to NISP when assessing the relative abundance of elements. This discussion is quite similar to Grayson's earlier (1984) discussion of problems inherent in MNI estimates as the basis for taxonomic abundances. Just as MNI corrects for disparities in element abundances across different taxa but is subject to sample-size and aggregation effects, so, too, does MNE correct for differences in degree of fragmentation across different elements of a given taxon, but it is subject to the same sample-size and aggregation effects as MNI.

Grayson and Frey (2004) used three large site archaeofaunas analyzed by others Elandsfontein, South Africa (Klein and Cruz-Uribe 1991), Kobeh Cave, Iran (Marean and Kim 1998), and Rond-Du-Barry, France (Costamagno 1999) to explore this issue. They showed that a "normed NISP" ("the skeletal part NISP values divided by the number of times the relevant part occurs in the skeleton of the animal involved," Grayson and Frey 2004:29) correlates so highly with both MNE and MNI ($r \geq 0.90$) that, regardless of whether one wants to examine species abundance or selective transport of elements, it should work equally well as these other, NISP-derived measures. Lyman (2008) agreed with Grayson and Frey's contentions regarding MNE, and used more examples of the tight relationship between NISP and MNE, to advocate for using NISP rather than MNE to assess skeletal element abundances by taxon. Lyman (2008:250–354) also engaged more with MNE as an index of fragmentation, when used in a ratio with NISP, which will be explored below. Moreover, methods for calculating MNE lack standardization, as pointed out by Lyman (1994) and Marean et al. (2001).

Insights from blind test experiments by Morin et al. (2017a, 2017b) have shed further light on which of these measures of element and taxonomic abundance offer estimates closest to actual known assemblage composition. Morin et al.'s (2017a) experimental program used a known input of fragmented , primarily of red deer/North American elk, to assess both the replicability and accuracy of element and taxonomic identification among analysts, as well as the relative performance of zooarchaeology's three main quantitative measures of abundance: NISP, MNI, and MNE. Their research reported not only on overall experimental results but also on the relative success of region-by-region identifications (e.g. long bone epiphyses versus diaphyses) and explored the possible sources of poorer outcomes. Chapter 9 reported on Morin et al.'s inter-analyst performance in identifying large, fragmentary assemblages produced by marrow extraction and by bone grease production. This section focuses on two other experimental results: first, the overall success of NISP, MNI, and MNE in estimations that approach those of the original experimental "inputs" and second, variations in successful element frequency estimates for various segments of the ruminant bodies in relation to the actual frequencies of elements and individuals in the experimental set.

Of special interest is the performance of NISP, MNI, and MNE respectively in identifying fragmentary long bone diaphyses to skeletal element. Some zooarchaeologists working with Pleistocene archaeofaunas developed strong arguments for identifying fragmentary long bone shafts and methods to do so (Chap. 21).

Their motivations stemmed from naturalistic and experimental observations of hyena bone processing. These indicated that long bone diaphyses – among the most durable components of the mammal skeleton – remained after hyenas had consumed epiphyses (Chap. 12, see also Chap. 17). Hyenas were considered to be proxies for other large carnivores, such as wolves, inhabiting much of Pleistocene Eurasia and Africa during the span of human evolution. Thus, the reliability of identifications based on diaphyseal fragments emerged as a particular concern to those working where large carnivore impacts on bone assemblages were a likely taphonomic factor.

The three blind test participants in the Morin et al. experiment outlined in Chap. 9 were asked to calculate NISP and MNI according to an instruction guide, which also asked them to record specific landmarks and regions of long bones for reckoning MNI (see Morin et al. 2017a:899-900 for details). MNE values were derived from summing MNI for left and right sides. Thus, all three participants followed the same estimation procedures.

Outcomes of the experiment included some that contradicted longstanding assumptions. The much higher levels of fragmentation of the bone grease production set were expected to lead to lower rates of accurate specimen identification (NISP) in this sample versus the marrow cracking assemblage (Cannon 2013; Marshall and Pilgram 1993). Instead, results were comparable. Morin et al. chalk this up to the fact that bone grease manufacture produced more epiphyseal fragments, which were more identifiable.

Statistical assessment of estimation results showed that MNE was straightforwardly replicated among the analysts *and* generally provided more accurate estimates of original relative skeletal abundances than did NISP. Morin et al. explored the sources of NISP's poorer performance by assessing the effects of differential fragmentation rates among each long bone, discussing the implications of this inter-element variation for specimen identifiability. Different long bone elements were shown to break consistently into divergent numbers of fragments (Morin et al. 2017a:925, Table 18). This was interpreted as a major factor responsible for differing levels of long bone identifiability. However, the relative identifiability of various elements in the marrow cracking assemblage differed from those in the bone grease extraction assemblages, arguing against using an element-specific constant, or correction factor, for fragmentation rates (Morin et al. 2017a:925).

In sum, the performance of both NISP and MNE in estimating original skeletal element abundances *across analysts* was generally quite good, with MNE being generally better and more easily replicated among analysts than was NISP. However, the performance of *any* measure in abundance estimates using long bone fragments, where NISP did especially poorly, a special concern for those concerned about carnivore attrition in archaeofaunal assemblages.

Morin et al. (2017a:927) stress that their results should not be taken to suggest that MNE is a cure-all for quantifying relative skeletal abundances, for the reasons already cited by Grayson (1984) and Lyman (2008). They stress that MNE is susceptible to the same problems as MNI, highlighting its potential to inflate the importance of rare specimens in relation to numerous ones. The authors conclude with a call for greater standardization in recording MNE, MNI, and even NISP, as these will continue to be used as important measures of abundance in their application to different problems.

In a second article, Morin et al. (2017b) explored MNE's tendency to inflate the importance of low-NISP elements across 58 Middle and Upper Palaeolithic archaeofaunas from Western Europe. Their approach differed from that of Grayson and Frey (2004) and of Lyman (2008) because they monitored the relationships of the NISP to MNE across 24 classes of skeletal parts. NISP-MNE relationships were explored by comparing coefficients of determination in linear and curvilinear (power function) regression analysis. A better fit with the latter implies that the two measures do not increase commensurately as NISP increases. They found that in very small, NISP≤50 samples, power functions better described the relationship of NISP to MNE, whereas the higher the NISP, the more linear was the relationship, although some elements sustained a strong curvilinear relationship. Morin et al.'s (2017b) details of high- and low-scaling exponents for different elements and their observations on the behavior of different skeletal elements in the NISP-MNE relationship bears careful attention by analysts because these create expectations for the "behavior" of different fragmented long bones.

Finally, Morin et al. (2017b) introduced an alternative measure of element abundance: Number of Distinct Elements (NDE). This is a tally of the number of times at least 50% of a stipulated diagnostic landmark occurs in a sample, with each occurrence scored as "1." Landmarks for each element for cervid and bovid long bones are listed and illustrated, with some supplemental instructions for estimation, in the article (Morin et al. 2017b: Table 4, Figs. 9–11). The 87 NDE landmarks are not an exhaustive list of osteological landmarks but rather those that the researchers, all of whom have extensive experience with Pleistocene archaeofaunas, often encounter in these samples. They assessed the accuracy of the NDE using the same experimental marrow cracking and bone grease extraction assemblages as was used in their earlier study. Rank order correlation coefficients between element abundance estimates based on NDE tallies and the actual element abundances of the inputs were very strong (Morin et al. 2017b: Table 5), although, again weaker for long bone regions than for other elements (Morin et al. 2017b: Table 6). They state, "These observations suggest that the NDE is as robust as MNE for estimating skeletal, and possibly, taxonomic abundances." (Morin et al. 2017b: 956). Advantages enumerated for this method are:

1. NDE counts are more easily calculated than MNE counts.
2. The measure is inherently more standardized than the MNE method.
3. NDE values are expected to increase linearly with NISP sample size.
4. The NDE approach does not suffer from the aggregation problems.

The authors add that the NDE approach is similar to that developed recently to calculate mollusk abundances in archaeomalacological samples (Harris et al. 2015; Mason et al. 1998).

Given my own present inclination to opt for using landmarks in element identification and quantification (Chap. 10), I recommend that interested researchers road test this method as a measure of skeletal element and taxonomic abundance. As the authors state, one "sacrifices" the NDE method requires is excluding identifiable fragments that lack one of the small number of landmarks listed for each larger element. However, this does not mean that researchers must discard such specimens from their datasets, nor that such pieces would not be useful in zooarchaeological analyses *other than measuring abundances*. For example, if one were interested in evidence for handling of deer elements, one could use all specimens to assess cutting edge and percussion damage to skeletal elements, so as not to exclude specimens that testified to consistent patterns in the placement of hammerstone impacts, chops, cuts, and so forth. The tradeoff here is that one may gain a quickly recorded method of quantification that is not subject to aggregation and sample size effects in the same ways as MNI and MNE, and is more reliable in its abundance estimates than NISP appears to be. The NDE approach could be used by cultural heritage/resource zooarchaeologists without much additional work, thereby adding valuable, comparable data on species abundances, and even element abundances, for sites that they must work with efficiently and swiftly. One concern about the NDE parallels that raised by Faith and Gordon in (2007, Chap. 21) regarding Marean and Cleghorn's recommendation to restrict inter-assemblage comparisons to high-BMD specimens only. Faith and Gordon noted that this might reduce some sample sizes so much that they are liable to Type I and Type II errors. This is one of the reasons it might be good to "road test" NDE with such issues in mind.

18.4 What Do You Want to Do, What Tools Do You Need?

Confronted with the problems of NISP on the one hand, and those of MNI and MNE on the other, plus the prospect of learning how - or if - to use NDE, a prospective zooarchaeologist may be tempted to consider a new career in Medieval French literature. But before rushing out to buy a copy of *Larousse Etymologique*, the analyst should at least consider some other factors – that is, act "thoughtfully."

For any given sample, whether NISP for different taxa is likely to have differed from the outset, due to differing skeletal element counts, or to have been impacted differently by taphonomic processes, is empirically investigable. One can, for example, start simply by comparing the skeletal element counts of species one knows are in a sample. One can learn how many skeletal elements make up a rock cod skeleton versus the counts for a sea otter skeleton. The cod and the otter also diverge in the ways their remains respond to taphonomic processes. A landmark-based system may well be the best way to estimate their relative abundances in an archaeofauna sample containing both taxa, while still keeping an eye on other measures such as NISP. An analyst comparing mammals and birds also will need to consider differential bone count and taphonomic effects on counting units (Bartosiewicz and Gál 2007; Lyman 2015). In the African Neolithic archaeofaunas I have analyzed, nearly all specimens came from one zoological family, the Bovidae.

The number of skeletal elements in a bovid body is the same, regardless of the species, and though some bovids are the size of terrier dogs, while others weigh a metric ton, the responses of those elements to stresses pre- and postmortem will fall along a spectrum rather than radically diverge. In such cases, I can assess whether NISP would work as well as MNI or MNE in comparisons of element abundance, if I did not go back and score NDE for the specimens.

One must also consider intertaxonomic differences in human processing effects on all abundance statistics. For example, the archaeofaunas used by Grayson and Frey, as well as by Lyman, in their explorations of the efficacy of NISP are dominated by ungulate remains, which come in different sizes but which people handled in remarkably similar ways. I presently work with coastal California archaeofaunas that combine deer, rabbits, and seals in the mammal component. People intensively fragmented bones of deer long bones to a modal size of 2 cm, slightly damaged rabbit bones, probably as a by-product of processing these much less robust skeletons, but seldom broke anything except the crania of the seals. Seal and sea lion bones are very densely packed with bone tissue that serves as "diving ballast" for their blubber-insulated – and therefore buoyant – bodies. Their long bone marrow cavities are absent or so small as not to repay the work of opening them, especially since their blubber offers greater returns in fat. In such samples, NISP seriously overrepresents deer relative to pinnipeds, and producing MNE estimates presents disparate challenges. However, fragmentation is empirically investigable by a number of analytic procedures, as will be addressed in Chap. 20. In terms of reckoning relative element abundances, I believe a landmark-based system in fact would make explicit the approach I already use in poring through 1–2 cm deer specimens for element-distinctive features.

18.4.1 Units of Measure and Research Goals

To sum up, one's research goals influence the statistical tools appropriate for the job. As Lyman (1994:44) put it, "We must be clear about the target population the properties of which we wish to infer, and, thus we must consider how the quantitative units we use are related to those properties." Nearly all of Grayson's and Lyman's significant research on North American archaeofaunas has concerned changes in taxonomic abundances over time. They considered that NISP, for all its failings, was a suitable tool for monitoring such shifts, a decision they might wish to reconsider in light of recent experimental research (Morin et al. 2017a, 2017b). However, if a zooarchaeologist is focusing on household culinary processing and consumption patterns, one may wish to use other quantitative tools, such as MNE and fragmentation indices (Chap. 21), taking into consideration all the cautions outlined in this chapter and Chap. 10 In all cases, Lyman's (2008:221) advice to those using any form of quantification holds: "We must be explicit about how we count, whether we count NISP, MNE, MNI, or any other measure."

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Chapter 19

Skeletal Disarticulation, Dispersal, Dismemberment, Selective Transport

This chapter focuses mainly on one form of aggregate data analysis that has occupied many zooarchaeologists for over four decades: using element frequencies and, to a lesser extent, cut-marks to infer selective transport of larger animals' body segments from where they were acquired to other locales. As with zooarchaeological research on bone fracture, cut, and percussion marks, one line of investigation in this area was driven by debates over early hominin behavior and adaptation. Another line of butchery and transport research centered on of ancient Americans' hunting practices, both Paleoindian and later (Chap. 2). Related actualistic research has focused mainly on butchery by nonagricultural, hunting peoples. Even studies of agricultural peoples' uses of animals have largely focused on hunted prey (Crader 1983). One exception is my own work on butchery by agropastoral Dassanetch people and by poor Dassanetch who lacked livestock and were of necessity farmer-fisher-hunters, foraging for wild animal food to supplement family grain supplies (Gifford 1977, 1978; Gifford-Gonzalez 1989). More attention has been paid to primary butchery at kill sites or other field acquisition sites than to secondary butchery or culinary butchery practices. Research on butchery was so narrowly focused in part because some studies were framed as direct responses to Binford's assertions about early hominin foraging. Others were motivated by a sense of urgency to document foragers' lifeways before rapidly changing political and economic circumstances further altered their hunting and gathering ways of life. The relatively well-funded and active cohort of zooarchaeologists working on human origins set the terms for much methodological debate in the zooarchaeological literature.

This chapter focuses most on skeletal element frequencies rather than cut marks because I am convinced by Lyman's (1995, 2005) case that, of all hominin-inflicted bone surface modifications, cut marks are the least desirable single-variable bases for broader behavioral inferences (Chap. 14). Besides these reservations about the inferential limits of aggregate cut mark data, another emergent question is how best to represent the degree to which an archaeofaunal assemblage is cut marked, given that varying degrees of specimen fragmentation will affect calculation of cut mark rates. Abe et al. (2002) discussed the best method for quantifying cut mark

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https://doi.org/10.1007/978-3-319-65682-3_19

frequencies in consideration of the fact that different samples may diverge markedly in their degree of fragmentation. They give the simple example of a complete femur with three cuts (2 proximal, 1 on the shaft), in which the ratio of cut marks to the complete femur would be 3:1 or .30. They then represent the same femur with its shaft broken into 6 diaphyseal fragments, one of which bears the cut mark, plus the proximal (with 2 cut marks) and distal ends. In this case, the ratio of cut marked fragments expressed as NISP (=8) to cuts is 3:2 or .375 (their simple example did not consider the further complication of a break creating several fragments of a single cut mark).

Abe et al. (2002) also posit that taphonomic effects can further affect cut mark frequency estimates, noting that cuts will preferentially be preserved on the more durable sections of elements. They note that fragmentation from these combined sources can be expected to vary across assemblages, according to the intensities of human processing and other taphonomic impacts. For these reasons, they argue, MNE is the more reliable indicator of cut mark intensity, because it norms the count of fragments toward the original "input" of elements. They further suggest using an ArcView® GIS-based analysis to estimate MNE, as discussed in relation to element survival in Chap. 21.

These complications have not stopped some from continuing in pursuit of behavioral inferences from cut marks. James and Thompson (2015) review ongoing controversies over these and other bone surface modifications, offering insights into their root causes and some suggestions for resolving those that stem from the unstandardized and inconsistent definitions of modifications.

Is hunter-centered butchery and transport research done relevant to archaeologists studying remains of domestic animals? Crabtree (1990), O'Connor (2000), and Orton (2012) have all emphasized the value of methods and generalizations drawn from such research for analyzing archaeofaunas from food producing and socially complex societies. The literature details the tactical problems that different-sized animal bodies present to their butchers, and zooarchaeologists studying domestic species must also consider the challenges faced by handling different-sized animals. Sedentary food producers seldom butcher large domestic animals in their homes, and they must make transport decisions based on trade-offs between nutritional gains and the transportability of various carcass segments. In urban food systems, larger animal bodies are subdivided and circulated as commodities (Zeder 1991), but when, where, and how this happened in an archaeological case must be investigated. Social asymmetries may govern individuals' access to different cuts of meat, even in less complex societies, a topic taken up in more detail in Chap. 25. Although embedded in a different web of considerations, transport decisions nonetheless determine the sequence of actions that move a cut of meat from carcass to cook pot. It thus behooves all zooarchaeologists to consider the literature on field butchery and transport.

Three sections of this chapter contextualize the study of carcass subdivision and transport. The first offers some definitions to be used in this and later chapters and again advocates a *chaîne opératoire* approach to butchery, which focuses on the *products* of a temporally – and often spatially – extended process. The second section provides a baseline for studying human butchery by outlining intrinsic anatomical constraints affecting disarticulation, and hence the uniform challenges to dismemberment faced by both tool-using humans and nonhuman carnivores. The last section reviews zooarchaeological research on butchery and transport in Africa and the Americas, focusing on key debates and on actualistic research that have contributed important findings and perspectives over the last half-century. In the interests of brevity, it omits Australia and East Asia. This section sets the stage for Chap. 20, which deals in detail with methods for calibrating the relative nutritional values of different body segments, as this may affect human transport decisions and hence element frequencies in archaeofaunas.

19.1 Initial Definitions and a Conceptual Framework

Chapter 12 discussed reasons why carnivores transport body segments and stressed that both transport *and* consumption sequences reflect a greater than one-to-one size ratio of the consumer and the consumed. This "given" should be kept in mind throughout this chapter and the next. To gain a clearer view of these topics, some definitions are required. I call the natural process of postmortem disaggregation of elements of a skeleton *disarticulation*, which contrasts with the active division of a carcass by human or nonhuman actors, *dismemberment*. As noted in Chap. 15, humans' tool-mediated subdivision of animal carcasses is often called "butchery," which Lyman (1987: 252) defined as, "the human reduction and modification of an animal carcass into consumable parts." Chapters 14 and 15 described distinctive signatures of such handling, which can involve *evisceration*, *skinning*, *dismembering*, *defleshing* (or *filleting*), and other handling (Lyman 1987: Table 5.2). O'Connor (1993) stressed that butchery can also entail stockpiling selected elements for tool manufacture, and I would add, other elements being reserved for fuel (Chap. 15). I prefer "carcasses processing" or "carcass handling" to "butchery," in part because these phrases link to terms used in behavioral ecology for other organisms' costs in handling their prey (24).

19.2 The Baseline: Vertebrate Body Structure and Disarticulation

Natural skeletal disarticulation and dispersal are largely governed by an animal's anatomical organization, which evolved to support the living organism yet also determines much of how body segments disarticulate after death. Human and nonhuman actors' tactics for dismembering vertebrate bodies are structured by these same anatomical constraints (Chap. 5). After a vertebrate's death, soft tissues decompose, facilitated by action of microorganisms and larger invertebrates (Chap. 16) and, as the connective tissues of articulations between skeletal elements degrade, bones of the skeletal unit begin to dissociate (Lyman 1994; Micozzi 1991). Notwithstanding invertebrate activity, this decomposition is largely a passive process because these actors cannot actively move body segments. Vertebrate taxa can be expected to vary in their sequences of disarticulation according to the relative strength of their taxonomically distinctive joint construction, which in turn results from the species' feeding and locomotor adaptations.

Lyman (1994:146) reviewed the role of joint types play in facilitating or impeding the rate at which given articulations come apart. Anatomists distinguish two overall joint types: *synovial joints* and *fibrous joints*. Synovial joints permit movement of body segments in one or more planes. They are composed of a connective tissue joint capsule enclosing synovial fluid, which acts as a lubricant for cartilage plates on the epiphyses of each articulating element, as well as enclosing the joint's ligaments. The range of motion of the joints depends upon the shape of the joint surfaces. Fibrous joints permit little movement between the joined skeletal elements. The strongest of these are cranial sutures, which in adult individuals ossify completely, but which, because of their interlocking sutures, do not readily disarticulate even in their unfused state. Symphyses have a cartilage plate between the two articulated bones, permitting slight joint mobility. The mandibular symphysis begins as such a fibrous joint, and it remains unossified in some mammals, such as ruminants, while ossifying in others, such as primates and equids. The mammalian pubic symphysis is another cartilage-based fibrous joint; in females, the cartilage permits widening of the pelvic outlet during birth. Cartilage-to-cartilage articulations of ribs to the sternum are also classed as fibrous joints.

Some vertebrates' long bones are covered by sheets of heavy fibrous tissue, such as the radius and ulna in birds and in those mammal species having these bones as independently mobile skeletal elements. Bones joined by fibrous articulations remain together long after death. Fibrous joints such as those of the radius and ulna will disarticulate with the decay of the connective tissue, and are more readily opened by consumers than are sutures or symphyses.

19.2.1 Natural Ungulate Disarticulation and Dispersal Patterns

In passive disarticulation of a vertebrate body, skeletal elements slowly disaggregate spatially. In the absence of other influences, gravity contributes to some dispersal of skeletal elements from their original, articulated, anatomical relations. However, animal bodies seldom exist in the absence of other influences. Dismemberment by carnivores, bone collection by rodents, disturbance by ungulate traffic, or transport by flowing water may influence the sequence and degree to which body segments and bones disperse.

Hill and Behrensmeyer (Hill 1979; Hill and Behrensmeyer 1984) documented disarticulation in zebras, three wild antelopes, domestic cattle in East African landscapes. Their aim was to use these "natural sequences" as a baseline for analyzing

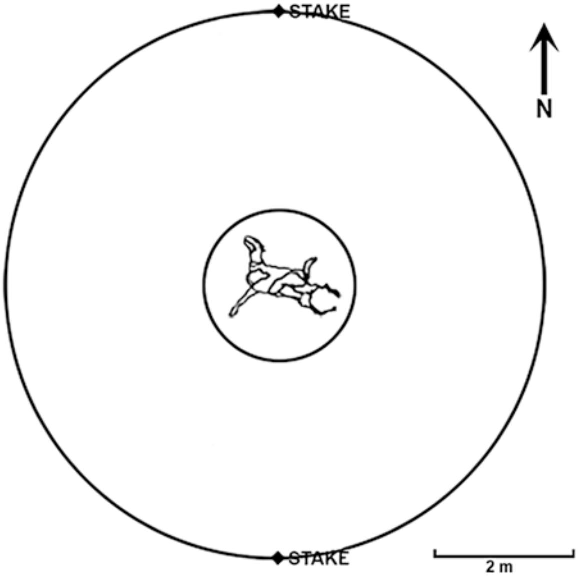

Fig. 19.1 Postmortem disarticulation and dispersal history of a zebra, East Lake Turkana, Kenya. October 1973, body encountered as a recently killed carcass that swiftly mummified, with dried skin and flesh holding it together. See text for details. (Illustration by author)

taphonomic effects in paleontological and archaeofaunal accumulations (Hill and Behrensmeyer 1985). For the taxa surveyed, some consistent patterns of disarticulation occurred, the forelimb detached from the thorax first in all cases, with variable subsequent detachments according to the taxon: the mandible detached from cranium, and the scapula from humerus, in second or third orders, depending on species, and other joints diverged in their order of dissociation in bovid *versus* equid skeletons.

Lyman (1994:144) cautioned that, because the Hill and Behrensmeyer studies were done in natural landscapes, where unobserved biological and meteorological processes could have affected the order of disarticulation, they should not be considered a “pure baseline” for passive disarticulation. Lyman (1994: Table 5.5) analyzed their data and found underlying regularities, with synovial joints tending to disarticulate before fibrous ones.

Figures 19.1, 19.2, 19.3, and 19.4 presents a “time-lapse” view of disarticulation, dispersal, and dismemberment of a common zebra (*Equus quagga burchelli*) carcass that I monitored on a littoral plain on the northeastern shore of Lake Turkana for 10 years after its death in October, 1973. At the time of its death, Taphonomic Specimen 4 (T4) lay about 30 m from the lakeshore. Carnivores had consumed the zebra’s hind limb flesh and entrails, but the balance of its skin and flesh swiftly mummified in the hot, dry climate, becoming less appealing to consumers (Fig. 19.1a). It served as a resilient chair for members of a Dassanetch foraging

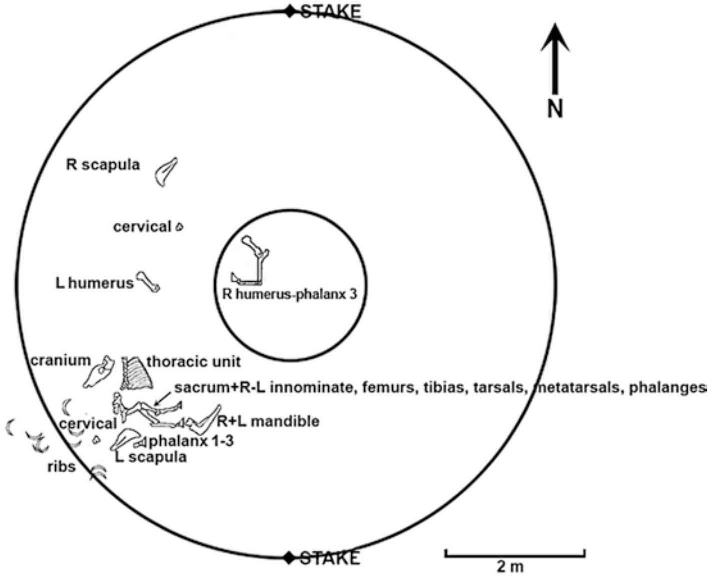

Fig. 19.2 April 1974, mummified skin and flesh were rehydrated by rains and swiftly consumed by invertebrate and mammalian carnivores. Elements were dismembered and scattered by larger mammalian carnivores. See text for details. (Illustration by the author)

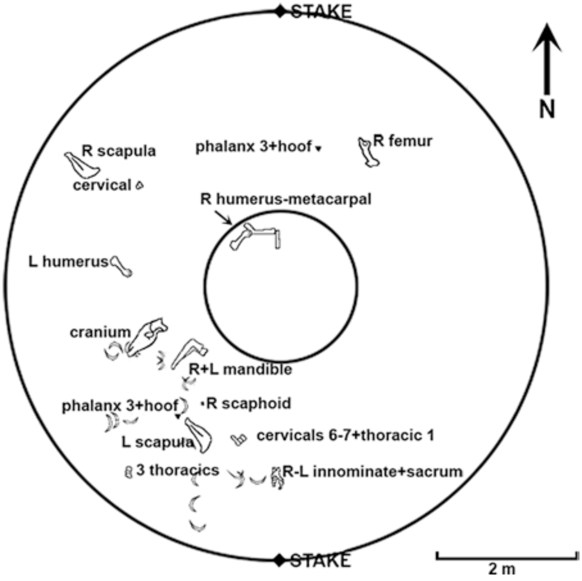

Fig. 19.3 August 1974, skeletal elements continue to disarticulate and be displaced by daily ungulate traffic. See text for details. (Illustration by the author)

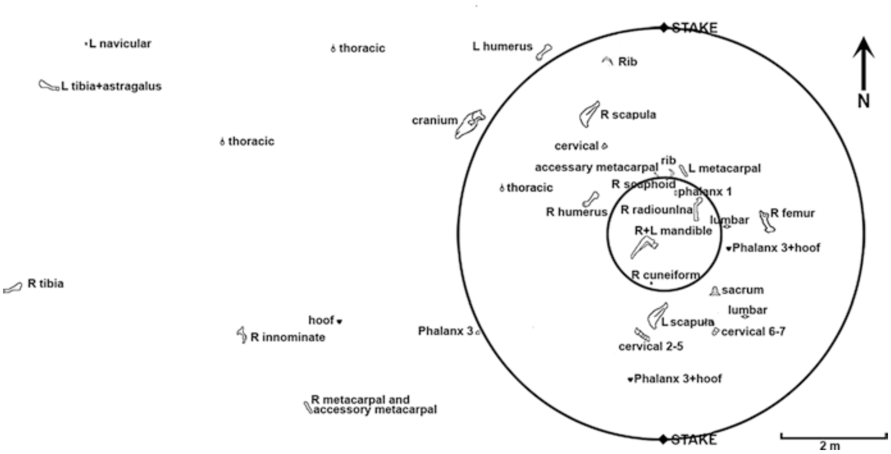

Fig. 19.4 September 1976, skeletal elements continue to disarticulate and be displaced by ungulate traffic. See text for details. (Illustration by the author)

group who camped around it a few months after its death. The carcass remained in its mummified form until April 1974, when heavy rains fell in the area. T4 rehydrated into an odorous but evidently very attractive meal for hyenas and jackals, whose tracks were seen in the mud around the carcass (Fig. 19.1b). Scarab beetles and other insects were active on the carcass. Within the a few days, the still-united axial skeleton was moved about 4 m southwest of its original location, clearly due to the action of larger mammalian consumers, and the mandible, anterior limb bones, and some ribs dissociated from it. Subsequently, passive disarticulation dominated, with more ribs and vertebral segments disarticulated by August 1974 (Fig. 19.2). A well-trodden game trail passed through what was becoming the T4 bone scatter, and herds of zebra and topi antelope coming down to drink at the lakeshore were a dominant engine of modest carcass-part dispersal, as well as trampling damage to skeletal elements. A recheck of this carcass in September 1976 (Fig. 19.3) revealed loss of many of the ribs and some other elements from the scatter, probably by bone-gnawing carnivores such as spotted hyenas, as well as further scattering and dispersal of elements. Thus, an array of biological and meteorological processes interacted with the T4 carcass over 24 months, some leaving traces on its elements and distributions and some not.

The Hill-Behrensmeyer sequence for ungulate disarticulation does not apply to all mammals, much less to other vertebrates. Different taxa possess specialized joints and associated soft tissue anatomy that can speed or slow joint separations. For example, the temporomandibular joint is among the first joints to disarticulate in humans and most herbivores. The structure of these species' jaw joints is relatively open, allowing up-and-down and rotary motion while chewing. When joint capsule tissues and surrounding muscle decompose, the mandible simply falls away from the cranium. By contrast, mustelids such as otters and minks rely on their jaws to seize and kill prey equal to or greater than their own body size. Their mandibular articulations are buttressed by growth of temporal bone around the mandibular condyle; even after all the soft tissues vanish, the cranium and mandible often remain tightly articulated. Mustelids can thus be expected to display a divergent sequence of disarticulation from the ungulates, as well as having more tool marks associated with removal of the jaw, if humans butcher them.

Zooarchaeologists have made taphonomic disarticulation studies on guanacos (Belardi and Rindel 2008; Borrero 1990), pinnipeds (Borella and Muñoz 2006), kangaroos (Reed 2009), and birds of various sizes (Livingston 1989) Weigelt's ([1927] 1989) classic work also offers much useful information on disarticulation across a range of species.

19.3 Carnivores and Carcass Dismemberment, Dispersal, and Transport

Nonhuman carnivores and humans transport vertebrate bodies or body segments from where they encounter them to other locations, with similar motivations: physical safety, shelter from the elements, or provisioning the young or other members of their social groups. Selective removal of body segments from a carcass normally occurs only when that animal's body cannot be transported whole to another place by the consumer, or where the resolution of social tensions within a group of consumers drives subdivision of the carcass. Joint strengths of vertebrate bodies interact with the abilities of consumers to remove and carry body segments away from the death site.

The intentional segmentation of an animal carcass, here called *dismemberment*, results from exertion of force to open joints and break large prey into smaller packets for transport. Both nonhuman carnivores and humans do this, but they approach this task quite differently. Unlike tool-using hominins, carnivores lack the means to sever tightly articulated joints in larger prey. They normally select body segments that readily come off a carcass. For hoofed animals, these are:

1. foreleg (with scapula);
2. mandible;
3. upper hindleg (with or without os coxae);
4. depending on the ungulate taxon, the lower hind leg (metapodials and phalanges) may be disarticulated and left at the death site during initial consumption.

Like human butchery, carnivore dismemberment of larger animal carcasses is an ongoing series of actions that can actually begin during kills, when parts of the prey's body may be dislocated or even wrenched off. It continues during initial feeding at the acquisition locale. As outlined in Chap. 12, carnivores feeding on animals equal to or larger than their own body size display a regular consumption sequence, in a trade-off between the nutritional gains offered by various tissues and their physical abilities to access them. In this process, dismemberment may occur; for example, eating the muscle masses around shoulder and hip joints may cause the limbs to dissociate from the trunk, even if the consumer is not actively wrenching at a leg. Carnivores may break down cartilaginous fibrous joints by gnawing on them. Once a body segment is detached, carnivores may transport it a few meters or several kilometers, depending upon their motivations. Transport of prey body segments over longer distances depends on situational, species-specific nutritional needs such as provisioning of dependent offspring or lactating females in refuges (Chap. 12).

19.4 Butchery: Tool-Mediated Carcass Dismemberment, Dispersal, and Transport

Humans may have been central-place foragers since the emergence of our genus. Foragers taking possession of animal bodies that outweigh them face the challenge of getting the body back to their home base. Human hunters and scavengers use a highly flexible set of tactics to do so, responding to many factors, which Lyman (1987) summarized. These include the weather and time of day when a species was acquired, variations in how many animals are killed or encountered, how many potential carriers are in the hunting party or can be called in to help, how far the hunters are from their ultimate destination, and whether alternate means of transport, such as pack animals, dog sleds, cars, or snowmobiles are available. Other temporal factors include the time of day a carcass is acquired, weather and other physical circumstances, and presence of scavenging animals capable of appropriating a carcass left in the field overnight. Binford (1978:81–83) reported a dramatic instance of Nunamiut butchers racing the breaking ice of the Anaktuvuk River when the mass kills of the northward caribou migration coincided with an very early spring thaw. Hunters were processing the carcasses across the river north of their residential camp and had been intending to transport body segments over the frozen river with their snowmobiles. As butchers worked, the loud cracking of river ice blocks signaled the imminent break-up, and they hurriedly segmented and carried carcass sections across the ice, skipping the fine-grained subdivisions applied in years that allowed a more leisurely approach.

One alternative to the usual pattern of bringing home the prey is simply to move households to the acquisition site for as long as it takes to consume and/or preserve the animal's flesh. This has been documented for mass kills of large animals such as bison (e.g. Denig 1930; Lowie 1922) and for use of very large single animals such as elephants and whales. The more usual practice for hunters acquiring animals in less imposing numbers or sizes is to move the prey, rather than the base of household operations. This entails tool-aided dismemberment of the carcass, which does not necessarily follow the sequence of passive disarticulation outlined earlier but rather conforms to the butchers' aims and the capacities of their tools.

The relative strengths of large prey articulations challenge human as well as nonhuman consumers when they seek to dismember body segments. It is a truism in zooarchaeology that tightly articulated joints are more likely to bear marks of the tool's intervention in the form of cut, chop, or sawing marks (Chap. 13). Human butchers can dismember synovial joints by cutting ligaments and other connective tissues around the joint, opening the joint capsule, and levering the joined elements into a "dislocated" position for final separation. Sutures and symphyseal joints require the heaviest intervention and may not be opened so much as fractured or chopped.

Some central considerations condition butchery decisions. In the parlance of modern postal services, dead animals are "dated materials," demanding processors' timely attention if they are to use them. Ethnographic cases caution against extending Western criteria to other cultures' food preferences; however, at some point, animal body parts become unusable as food. Binford (1978) reported that Nunamiut people consumed red marrow in the ribs of freshly killed caribou, but if the ribs were frozen for several months, they would simply strip and cook the muscle from them because they deemed their marrow was unpalatable after that span. Butchers routinely handle carcasses to isolate the intestinal tract and its contents to avoid contamination of flesh and other edible tissues that accelerate spoilage and pose health risks. Butchers extract and consume parts most likely to degenerate first (blood, brains, viscera) and specially handle tissues of intermediate "shelf life" and risks of transferring bacteria to meat – such as marrow (Friesen 2001) – keeping them away from meat intended for long-term storage, either to extend their palatability or to enhance their transportability. Realities of postmortem decay interact other factors, such as the number of animals acquired in relation to the number of consumers. If 50 people in a hunting group kill 150 bison during one spring day, intending to produce enough jerky for the summer, they are under pressure to speedily strip the carcasses in order to efficiently dry masses of meat. If 50 villagers slaughter and share one ox, subdivision of a single carcass among community members effectively eliminates pressure to extend the use-life of the animal's flesh.

Lyman's (1987) noted that all butchery operations depend upon available technological means for subdividing, transporting, preserving, and preparing carcass parts for consumption. This includes tools used in primary and secondary butchery, as Seetah (2008) explored in detail using the transitions in carcass segmentation enabled by different kinds of metal tools documented during European history. Whether transport of large animals' carcass parts depends on human carriers, pack animals, or vehicles will influence transport decisions, and each entails different strategic social and technological investments. Forms of culinary processing can affect field decisions about what to bring home and how to transport it (Gifford-Gonzalez 1993). In some ethnographically documented cases, the cooks were also the field butchers (see references in Gifford-Gonzalez 1993:189). In other cases, the primary butchers were hunters, but fully knowledgeable about the uses to which carcass parts will be put and process these accordingly.

Pastoralists, farmers, and specialized meat producers in complex societies normally have few "search costs" with domestic animals, but they still must organize the slaughtering of animals in a convenient locale in relation to their settlements, initial tissue extraction and carcass segmentation, and moving transportable units to other places. Traditional Maasai pastoralists in East Africa have habitual slaughtering localities outside their settlements, where they strip flesh from some sections of cattle carcasses and discard bones from those segments, carrying only soft tissues and selected bone-in units to the home camp for further processing (Mbae 1986).

The next section reviews the history of zooarchaeological butchery and transport studies.

19.5 Butchery and Transport Studies in Zooarchaeology

Readers seeking deeper historical context can turn to Lyman's 1987, "Archaeofaunas and butchery studies: A taphonomic perspective," also Domínguez-Rodrigo's 2002 "Hunting and scavenging by early humans: The state of the debate," for details on the earlier Africanist research. Since Dart, White, Wheat, Perkins, and Daly (Chap. 2), most zooarchaeologists have believed that element frequencies can reflect human decision-making during large animal butchery. Except for Binford's (e.g. 1978) investigations of Nunamiut animal use, butchery and transport research has shown a strong inclination toward studying the early stages of carcass acquisition and subdivision, focusing on "kill-site" archaeology. This matter will be taken up further in Chap. 20.

Through the 1970s, Frison and his students (e.g. 1970, 1974, 1978; Todd and Frison 1986) followed Wheat's lead in documenting regular patterns of carcass dismemberment, bone breakage, and selective transport from acquisition sites. They interpreted these cases as reflecting a strategy to maximize swift meat removal from many animals during short, intense butchery episodes, systematically documenting the carcass segmentation and intrasite distributional patterns.

19.5.1 First Wave Ethnoarchaeology of Butchery and Transport

Ethnoarchaeological studies in Africa in the early 1970s and elsewhere reported hunting, butchery, and transport strategies that diverged from those of North American bison hunters and from expectations generated by Perkins and Daly's classic article (1968) on *schlepp* effect (Chap. 2). Yellen's (1977) research on large antelope butchery by !Kung hunters in Botswana, where large animals were taken infrequently and usually one at a time, revealed other patterns of butchery and transport. !Kung hunters removed and discarded horns and digestive organs at the acquisition site during primary butchery and immediately consumed other organs and metapodia. However, they treated the remaining carcass quite differently from the mass kill pattern. Body segments were broken down into readily transportable units and, although some body segments were stripped of flesh to facilitate transport, all skeletal elements as well as flesh were carried home. This handling raised the question of whether differing acquisition circumstances or "cultural" factors governed foragers' approach to carcass subdivision, a discussion elaborated through by ethnoarchaeological research through the 1980s and 1990s.

19.5.2 Binford, Bones, and the Hunting-Scavenging Debate

Butchery and transport research intensified in the 1980s, as the extent to which early hominins were carnivorous and hunted for their meat emerged as a hot topic. In 1981, Binford combined element frequency and bone-surface modification analysis in *Bones: Ancient men and modern myths*, first reporting on his actualistic research among Nunamiut hunter-gatherers of the Brooks Range, Alaska, and then taking many colleagues to task for their interpretations of archaeofaunas. *Bones* articulated Binford's justification for an actualistic approach to elucidating archaeological data. Binford argued that element frequencies, combined with the placement of cut marks on skeletal elements, could testify to the nature of faunal processing activities at a locality, and by extension, to site function. Among Binford's central findings was that Nunamiut people, who engaged in highly efficient mass processing of caribou twice a year, nonetheless displayed considerable variability in their discard vs. transport of caribou carcass parts. He attributed this to their calculated responses to situational variations in the number of animals killed, size of the potential carrying party, availability of means of transport, and weather.

In the most controversial part of the book, Binford applied his methods to analyze other researchers' published zooarchaeological data, from Plio-Pleistocene through Paleoindian periods. His conclusions about site function and the behavior of earlier hominins often departed markedly from those of the primary researchers. In *Bones* and in later publications Binford asserted that all Eurasian and African hominins except anatomically modern humans were inefficient hunters (e.g. Binford 1983, 1984a, 1984b, 1984c, 1985; Binford et al. 1988). He reserved a substantial section for a critique of inferences about hominin hunting from element frequencies of medium to large ungulates at sites in the Olduvai Gorge, Tanzania. At the time he was writing *Bones*, Olduvai was the best-published set of ancient African data, with tables enumerating species and elements (Leakey 1971). In the Olduvai tables, limb bones were overrepresented compared to elements of the axial skeleton, including durable teeth. Binford (1981, 1984b; Binford et al. 1988), contended that the Olduvai element frequency data displayed an "inverse utility curve" (Chap. 20) – in other words, many low-nutrition elements. He argued that the data reflected hominins' scavenging the leavings of carnivore kills.

Even as Binford was framing his critique, some Olduvai collections were being reanalyzed according to contemporary standards. The excellent bone preservation at some sites, especially FLK 22 *Zinjanthropus,* dating to nearly 2 million years of age, permitted study of bone surface modifications, and stone-tool cut marks were first diagnosed in this archaeofauna (Potts and Shipman 1981; Bunn 1981).

Bunn, who along with Shipman and Potts had been reanalyzing the FLK 22 *Zinj* archaeofauna, responded that these accumulations resulted from hominins' transport of meaty limb bones from kill sites as hunters or "active scavengers" who appropriated carcasses from predators while meat remained on the limb bones (Bunn 1986; Bunn and Ezzo 1993; Bunn and Kroll 1986, 1988).

Zooarchaeological debate over whether early genus *Homo* acquired large ungulate body segments by hunting or by scavenging continues to this day. In the late 1980s, it incorporated bone surface modifications, especially cut marks, as well as element frequencies as data, and other research teams joined the fray (e.g. Blumenschine 1988; Blumenschine and Marean 1993; Capaldo 1997; Domínguez-Rodrigo 1997b) with expanded archaeofaunal samples, as evidenced in Egeland et al.'s (2004) comparative study (Chap. 17). A thorough overview of this debate would make – and indeed has made – a book in itself and is beyond the aims of this one: a quick count of relevant, post-*Bones* publications in one decade-old review by Domínguez-Rodrigo (2002) yielded 219 independent citations! This controversy exemplifies the challenges of assigning behavioral meaning to aggregate archaeofaunal data: much of the argument centers on what counts as compelling evidence of primary access to a carcass, and on what grounds.

In sum, Binford's assertions and some of his uses of others' data prompted a wave of research on archaeofaunas associated with early members of the genus *Homo* in Africa and with pre-modern forms of *Homo* in Eurasia. Subsequent fossil hominin research, zooarchaeological analyses, and bone-isotope investigations have disproven many of Binford's assertions regarding hunting capabilities of Middle Stone Age hominins in Africa – now known to actually be *Homo sapiens* in the sites he analyzed – and of Neanderthals in Europe. Nonetheless, many zooarchaeological methods, including use of the %MAU estimate of element abundance, element-specific nutritional utility indices, and cut-mark placement analysis, were spurred by his publications. Binford's provocations also led to considerable experimental and ethnoarchaeological research on bone durability and surface modifications, as well as associated nutritional yields of body segments. While diverse, these studies address the underlying problem of reliably establishing the functional and behavioral meanings of skeletal element frequencies and bone surface modifications in archaeofauna (see also Lyman 2012).

19.5.3 Actualistic Research on Determinants of Butchery, and Transport Decisions

Later publications on hunters' field decisions that determine element frequencies and bone surface modifications in sites included research with San-speaking hunters of southern Africa (Yellen 1991a, 1991b; Bunn 1983; Kent 1993; Bartram et al. 1991; Bartram 1993b); the Hadza of Tanzania (Bunn et al. 1988; Bunn 1993; O'Connell et al. 1988a, 1988b, 1990; Oliver 1993; Lupo 1995, 2006; Lupo and O'Connell 2002); the Okiek of south-central Kenya (Marshall 1993); Efe "Pygmy" foragers in the Democratic Republic of Congo, then Zaïre (Laden 1992); and Bofi and Aka foragers in the Central African Republic (Lupo and Schmitt 1997, 2005). In the Americas, researchers worked with hunters, including the Aché of Paraguay (Jones 1983) and Chipewyan Indians in Canada (Jarvenpa and Brumbach 1983, 1995). O'Connell and Marshall (1989) worked with hunting patterns and site formation among the Alyawara of central Australia. Domínguez-Rodrigo (1997a) undertook experimental observations on processing by expert Maasai and Mwalangulu butchers who were supplied with stone tools and carcasses with differing levels of prior carnivore access. Such studies were complemented by actualistic research on carnivore effects on element frequencies and their distinctive bone surface modifications, discussed in Chap. 12.

19.5.4 Hadza Research on Transport Decisions: Evolution of Methods

Research by two research teams with Hadza foragers of Tanzania merits detailed examination because its internal debates have proved useful in further defining the contexts of field butchery and transport decisions. O'Connell and colleagues (1988b, 1990) worked with Hadza groups near Lake Eyasi, employing a behavioral ecological framework. Their study of butchery and transport initially focused on the contexts of field transport and discard decisions, rather than upon site-focused assemblage formation. Later, Lupo (1994, 1995, 2001) published on bone assemblages collected by this research team from varied site types. O'Connell et al.'s data indicated that Hadza butchers often stripped limb bones of their flesh, cooked and broke long bones open for marrow, and discarded the fragments in the field, only transporting meat stripped from long bones to their residential camps. This contradicted the *schlepp* effect assumptions embedded in much zooarchaeological literature (Perkins and Daly 1968), but accorded with Yellen's earlier observations of !Kung transport practices.

About the same time, Bunn et al. (1988), working with other groups of Hadza foragers in the Lake Eyasi basin, published their research findings on butchery and transport. Members of Bunn's research team supplemented his initial research in the early 1990s, examining bone modifications (Oliver 1993) and comparing the Hadza data to butchery and transport data from Kua San-speaking hunters in Botswana (Bartram et al. 1991; Bartram 1993a, 1993b). These studies tended to support the generalization that groups that acquired one animal at a time transported most large skeletal elements, and that if any skeletal elements were discarded in the field, these would be long bones.

Disagreements emerged between the two groups of Hadza researchers over the meaning of the data. Both teams accepted that transport of nearly entire skeletons to residential camps was facilitated by their possession of boiling technology, which enables efficient retrieval of nutrients from bones of the axial skeleton. Bunn et al. (1988:443) maintained that, before boiling technology emerged, a limb-dominant pattern of transport probably held true. Thus, they argued that element frequencies produced by the Hadza and other contemporary foragers aren't necessarily relevant to analyzing the limb-dominated assemblages apparently created by early hominins.

Bunn's student Monahan (1998) undertook a comparative analysis of all Hadza datasets, demonstrating a "low limb *schlepp*" in all, and arguing that consistent long bone meat-stripping and marrow extraction in the field were part of a "weight-minimization" strategy. He further argued that this outcome might stem less from boiling technology and more from the Hadzas' being the top predators in the modern Eyasi ecosystem, with unlimited time at the butchery locale to dismember, deflesh, and extract nutrients. Monahan proposed that Olduvai hominins were unlikely to have ranked high in relation to other carnivores, with relatively less unhindered time at a carcass. Under such circumstances, he proposed, grabbing a leg and taking it well away to a safe refuge could have been the best "weight minimization" tradeoff.

Lupo (2006) worked through the combined Hadza dataset from a behavioral ecological perspective, specifically assessing transport decisions using central place foraging (CPF) theory (see Chap. 24). She argued that a skeletal element's associated nutritional value or "utility" in Binford's terms (Chap. 20), used by most zooarchaeologists, is not so informative as its return rate, an index now widely used in western North America. The return rate for a skeletal element is its associated nutritional yield *minus* the energy or time it takes a processor to fully realize that value. Lupo posited that, in each carcass acquisition event, "…Hadza partition field processing and transport costs in such a way as to minimize the amount of animal products discarded in the field and maximize the amount transported to a central location" (Lupo 2006:23). She argued that the food value associated with a skeletal element *after* field processing should predict its transport to a central place. She points out that relatively heavy long bones are easily stripped of muscle and broken to extract their marrow in the field, and it is efficient to discard them there. By contrast, irregular bones of the axial skeleton require much more processing effort to retrieve flesh and fat, especially when they are uncooked, thus having relatively higher unrealized nutritional value after field stripping. This provides a strong motivation to transport them to camp, only reinforced by the presence of boiling technology at the central place, which frees nutrients in stews without laborious hand-stripping.

Lupo predicted that outcomes of documented cases of Hadza large-prey processing would situationally involve a trade-offs among field processing effort and costs of transporting the carcass, according to the acquisition site's distance from camp and the benefits realized by doing so. To assess these predictions, Lupo selected two prey species, female impala (*Aepyceros melampus*) and female zebra (*Equus quagga burchelli*), because a good number of acquisitions of each species existed in the combined dataset.

Lupo (1998) had previously experimentally defined return rates for these species and used these in conjunction with each documented instance of acquisition and transport to assess whether element food utility (Chap. 20) or return rates better predicted Hadza transport of prey parts to the central place (base camps). The impala data showed a strong positive correlation between the time taken to retrieve nutrients from a skeletal element and its rate of transport to the central place, with discard of long bones in the field and transport of the axial segments to camp for stewing. By contrast, female zebra butcheries saw a relatively higher rate of long bone transport to camps, as well as higher rates of field discard of skulls and ribs. Lupo assessed these facts in terms of experimental observations on the unique challenges presented to marrow extraction by equid long bone construction, as noted in return rate experiments with the species. She noted that fully processing zebra long bones in the field would add 46 min to field processing episodes. Thermal processing frees marrow and fat from irregular medullary cavities that cannot readily be accessed manually, hence, transport of these relatively heavy elements makes sense. Lupo noted that the zebra skull and ribs are the skeleton's heaviest elements, and their stripped bone weight, when added to that of the long bones, may have dictated the documented decisions to discard them. In both taxa, nutritional utility values alone, without consideration of effort invested in retrieving the nutrients, did not predict transport behavior as well as did return rates. Return rates will be discussed in more detail in assemblages in Chap. 24.

19.5.5 Skeletal Versus Total Fat Values: Further Accounting for Transport Decisions

More than a decade earlier than Lupo's analysis, Emerson (1990, 1993) had advanced data and arguments that supplement and support Lupo's inferences regarding Hadza transport, in her own study of the nutritional benefits of skeletal elements of American bison (*Bison bison*). Emerson compared her findings with those of Binford and Jones and Metcalfe and also used her results to assess patterns of element representation in specific bison archaeofaunas. Emerson commented on the controversies over the Hadza data, as they then stood. Despite her focus on archaeofaunas that would have been products of mass kills, Emerson discussed the differences between processing and transport decisions in one-by-one acquisitions of large animals and those of mass-kills such as Nunamiut caribou harvesting and Plains bison kills. Anticipating later discussions by Lupo, who cites her, Emerson (1993) noted that the Hadza data can be seen as variations on themes of *maximal recovery* of carcass parts from animals encountered one-by-one, instead of the highly selective, nutritionally-driven "winnowing" of carcass segments seen at mass kills such as those of Nunamiut caribou predation or ancient bison kills. She asserted that a mix of four factors should influence large-animal transport decisions: (1) butchers' initial assessment of transportation constraints, (2) processing costs, (3) skeletal fat yield, and (4) snacking prior to return to the residential camp. While she did not specify return rates, Emerson was obviously considering precisely the variables that Lupo worked with in a more explicitly behavioral ecological framework.

Emerson also drew the useful distinction between "total fat," that is, the sum of all fatty tissue that can be recovered from a carcass (comprising subcutaneous, visceral, marrow, and bone grease) on the one hand, and skeletal fat (comprising fats intrinsic to the skeletal elements themselves, namely marrow and bone grease) on the other. She noted that, even when selective transport is required by the circumstances of a kill, axial segments may still be favored because considerable muscle and skeletal fat remain in these elements after muscle stripping, what Lupo (2006) referred to as "remnant animal products." Emerson (1993:142–143) used the bison data to show skeletal elements with relatively greater amounts of marrow have lower amounts of retrievable bone grease. Thus, if elements must be discarded at the primary processing site, it makes sense to snack on marrow there, discard the heavy and relatively unproductive long bone fragments that contained it, and to transport only high bone-grease skeletal parts. Vertebrae lack marrow and are exclusively reservoirs of bone grease. If total fat, including skeletal fat, is assessed, bison thoracic and lumbar vertebrae rank substantially above any elements of the appendicular skeleton, even femur and tibia. Therefore, if bone-grease rendering technology exists, and if fat retrieval is a major goal of animal acquisition, transport should favor those elements with high remnant skeletal fat content: the axial skeleton.

19.5.6 Are Transport Decisions Always Based on Field Conditions?

Chapter 15 noted that the focus on prey acquisition and primary processing alone, and not later processing phases, has pervaded zooarchaeological studies of transport decisions. This may stem from the archaeological cases that motivated some butchery-transport researchers. Plio-Pleistocene archaeofaunas in Africa are thought have been acquired before cooking or other processing strategies developed (Monahan 1999). Perhaps zooarchaeologists working with them assume a very short processing chain from animal acquisition to consumption, but this has seldom been explicitly articulated. Those of us working with archaeofaunas from later times have little excuse to avoid the ultimate aim of all animal-based foraging or keeping: its consumption phase and associated processing. We know that the addition of pyrotechnical food processing and technologically assisted nutrient retrieval, created increasingly complex operational chains involving animal bodies. Each stage involves costs and benefits that must be considered as part of return rates or other measures of effort. A product-focused, *chaîne opératoire* approach must include these stages in consideration of "butchery" (Gifford-Gonzalez 1993; Miracle 2002). Our zooarchaeological studies have yet to fully reflect this fact.

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Chapter 20
Calibrating Nutritionally Driven Selective Transport

Chapter 19 contextualized human decisions about which parts of larger animal bodies to carry to secondary locations and which to discard where they were initially processed, stressing that zooarchaeological inferences about transport primarily rest upon element frequencies. Zooarchaeologists' ability to assess nutritional values of different skeletal elements may elucidate these decisions. This chapter reviews zooarchaeologists' attempts to calibrate the nutritional yields of different body segments, which may motivate selective discard and transport of them. Chapter 21 discusses the other determinant of element frequencies in archaeofaunas: the differing durabilities of various skeletal elements in the face of destructive processes. In both cases, archaeologists have striven to find measures of bone's intrinsic properties, so that these can be applied in reasoning about element frequency patterning in archaeofaunas.

20.1 Making Sense of Element Frequencies: Nutritional Utility Analyses

As noted in Chap. 5, in the late 1970s and early 1980s, several publications brought a nutritional focus to archaeofaunal analysis. Speth and Spielmann (1983) introduced consideration of the uniform physiological needs of mammals living in strongly seasonal climates, especially the effects of seasonal variations in prey species' fat content, on human hunters prey and processing choices. Binford (e.g. 1977, 1978, 1980, 1981) wished to define "uniformitarian principles" to aid in exploring the evolution of modern human behavior, defining three lines of evidence likely to been uniform through hominin history, and to have affected the structure of archaeological sites: prey animal anatomy, regional ecology, and spatial consequences of the human body's size and organization on site structure. He accordingly advocated actualistic research with modern analogues and pursued research on all three lines among the Nunamiut people of the Anaktuvuk Pass area of the Brooks Range, Alaska.

D. Gifford-Gonzalez, *An Introduction to Zooarchaeology*,
https://doi.org/10.1007/978-3-319-65682-3_20

20.1.1 Constructing Relative Nutritional Values for Archaeofaunal Materials

In *Nunamiut Ethnoarchaeology* (Binford 1978), presented data on variable decisions regarding prey body segment transport according to specified situational factors. Binford presented a method for assessing the "economic anatomy" of prey animal bodies. The method was intended to be tool for reading the logic of butchery, transport, and discard behavior by hunters, and beyond that, for diagnosing activity and site type from archaeofaunal assemblages. The basics may be condensed as follows:

1. Skeletal element frequencies in archaeofaunas can be quantified.
2. Every element can be analyzed for its associated nutritional values.
3. Element frequencies in archaeofaunas reflect nutritionally motivated body segment selection or abandonment by butchers.
4. This in turn can suggest the function of the site yielding the archaeofauna – kill-butchery versus residential, for example.

Such understandings could permit insights into the planning depths with which hunters made decisions about using animals as food. Grayson (1989:643) succinctly described this approach: "people optimally forage across the body of an animal, as some believe people optimally forage across larger landscapes."

To provide key data for this analysis Binford (1978) devised a set of relative measures of associated nutritional values of caribou and sheep skeletal elements, which he named "utility indices." These numerically express the relative nutritional value of all tissues associated with a bone unit, 100.00 being assigned to the element with the highest nutrient yield and proportionate values for other units calibrated against this value. Binford commissioned nutritional analyses of two domestic sheep and a caribou body segments, to note meat, marrow, and bone-grease yields for each segment. These nutritional values served as the basis of indices for meat (Meat Utility Index), marrow (Marrow Index), and bone grease (White Grease Index) for the two species (Table 20.1).

Utility indices were based on individual bones, bone segments (e.g. proximal versus distal humerus), or to groups of bones (e.g. ribs, lumbar vertebrae). Binford's definition of carcass units stemmed from functional units observed in Nunamiut carcass processing (Binford 1978). He (1978:50, 62) assigned different MGUI values to proximal and distal ends of long bones, probably because Nunamiut often smash through the shafts of these elements when removing frozen limbs from meat caches. This type of carcass handling is not used regularly in other latitudes and led to later utility index modifications, discussed below. Binford combined all three values for each element or portion into the General Utility Index (GUI), a calculation found in Binford (1978:18–38). He noted that Nunamiut butchers often carried low-utility carpals, patellae, and tarsals from a butchery site as part of larger body segments. Reasoning that these low utility "riders" were transported because it would have cost butchers more time and energy to remove them in the field than it

Table 20.1. Binford's (1978, b:74, Table 2.7). MGUI values for caribou and sheep and Metcalfe and Jones's standardized (S)FUI values, and FUI values from Metcalfe and Jones (1988:492, Table 2). Radius and ulna values duplicate Binford's single set of values for both elements, listed as "radiocubitus"

Element	Caribou MGUI Base 100	Sheep MGUI Base 100	Caribou (S)FUI Base 100	Caribou FUI
Antler/horn	1.02	1.03	1.0	1
Cranium (CRA)	17.49	12.87	18.2	469 (235)
Mandible				
With tongue	30.26	43.60	31.1	1600
Without tongue	13.89	11.65	11.5	590
Atlas (ATL)	9.79	18.68	10.2	524
Axis (AXI)	9.79	18.68	10.2	524
Cervical (CER)	35.71	55.33	37.1	1905
Thoracic (THO)	45.53	46.49	43.3	2433
Lumbar (LUM)	32.05	38.90	33.2	1706
Sacrum (SAC)[a]	39.97	60.20	41.3	–
Innominate (PEL)	47.89	81.50	49.3	2531
rib (RIB)	49.77	100.00	51.6	2650
Sternum (STE)	64.13	90.52	66.6	3422
Scapula (SCP)	43.47	45.06	44.7	2295
p humerus (P HUM)	43.47	37.28	44.7	2295
d humerus (D HUM)	36.52	32.79	36.8	1891
p radius (P RAD)	26.64	24.30	25.8	1323
d radius (D RAD)	22.23	20.06	20.2	1039
p ulna (P ULN)	26.64	24.30	25.8	1323
d ulna (D ULN)	22.23	20.06	20.2	1039
Carpals (average)	15.53	13.43	12.7	653
p metacarpal (P MC)	12.18	10.11	9.0	461
d metacarpal (D MC)	10.50	8.45	7.1	364
p femur (P FEM)	100.00	80.58	100.00	5139
d femur (D FEM)	100.00	80.58	100.00	5139
Patella (PAT)[a]	82.37	66.29	81.4	–
p tibia (P TIB)	64.73	51.99	62.8	3225
d tibia (D TIB)	47.09	37.70	44.1	2267
Astragalus (AST)	31.66	23.08	27.7	1424
Calcaneus (CAL)	31.66	23.08	27.7	1424
Tarsals (TAR)	31.66	23.08	27.7	1424
p metatarsal (P MT)	29.93	15.77	19.5	1003
d metatarsal (D MT)	23.93	12.11	15.4	792
Phalanx 1(PHA1)	13.72	8.22	8.6	443
Phalanx 2 (PHA2)	13.72	8.22	8.6	443
Phalanx 3 (PHA3)	13.72	8.22	8.6	443

[a] Not listed by Binford, but MGUI value calculated by averaging distal femur and proximal tibia MGUI values, per Binford's treatment of "riders." See discussion in Metcalfe and Jones (1988:490–491). Values in parentheses in Metcalf and Jones's FUI are considered more realistic estimates, due to the high proportion of cartilage in the cranium originally weighed as usable meat

did to carry them, Binford modified the GUI to take this into account. He adjusted the GUI of “riders” by averaging their actual GUI with that of their adjacent, higher-value elements, producing the Modified General Utility Index (MGUI) for each unit (Table 20.1).

20.1.2 “Utility Curves”

Binford expected patterning in archaeofaunal assemblages to reflect choices based on such economic anatomy as indexed by MGUI, with highest-ranking body segments transported away from carcass acquisition locales at differentially higher rates than lower ranked ones. Based upon his experience with the Nunamiut, he argued that carcass processing in different seasons and with varied numbers of animals acquired should be expected to produce strategic variability in element frequencies and associated processing marks. He stipulated that, within each seasonal situation, strong regularities should exist in the carcass segments transported to residential sites and those left behind at kill/butchery sites, the results of reiterated, rational decisions by hunters and their households.

Binford constructed hypothetical models, or “utility curves,” for with relative element frequencies in assemblages at different site types, usually expressed as %MAU (Chap. 10) plotted against MGUI values in an x-y plot. He argued that mass kill-butchery sites, where low utility elements would systematically be discarded, would display an “inverse bulk utility curve,” with high frequencies of low MGUI elements, and low frequencies of high utility elements (Fig. 20.1). More selective butchery and transport tactics, Binford argued, would produce an “inverse gourmet utility curve,” with the same high frequencies of low MGUI elements but in addition higher frequencies of elements with middling MGUI values, reflecting a focus on the very highest-utility elements (Fig. 20.1). He predicted that residential bases would display the inverse of element frequency patterns from kill-butchery sites: “bulk utility curves” (Fig. 20.1), essentially the mirror image of inverse bulk utility curve, or “gourmet utility curves” (Fig. 20.1).

To assess these predictions, Binford tabulated element frequencies from documented Nunamiut kill-butchery sites, hunting stands, and residential encampments. He sometimes hand-drew curves to his x-y point plots of %MAU to MGUI (Fig. 20.2), but he never calculated correlation coefficients nor fit curves via regression analyses. This would have been problematic, given the ordinal nature of the utility index variables. Binford demonstrated that element representation at Nunamiut mass kill-butchery sites generally matched the “Inverse Utility” curve (Fig. 20.2), which supported his predictions. On that basis, he asserted that a utility-curve approach was a useful tool for exploring transport choices, and hence site function, in archaeological cases. However, residential sites did not produce a mirror image of the “Inverse Utility” pattern, nor have they in other ethnoarchaeologically documented cases, as will be discussed later in this chapter.

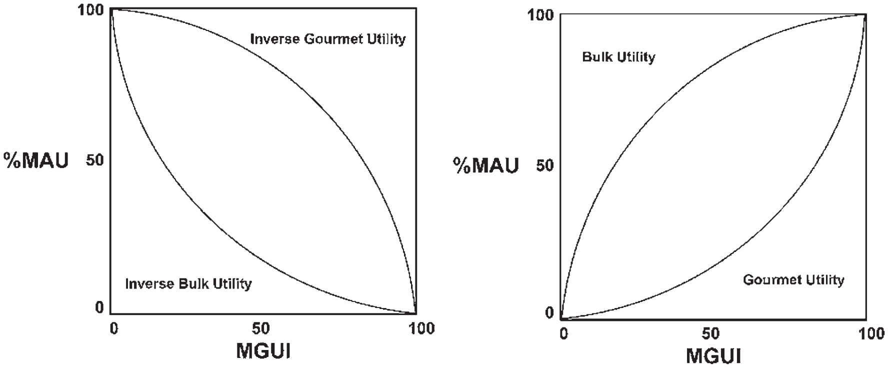

Fig. 20.1 *Left***:** schematic representation of Binford's "inverse bulk utility curve" and inverse gourmet utility curve, with element frequencies indexed by %MAU against MGUI. *Right***:** schematic representation of Binford's bulk utility and gourmet utility curves, the mirror-images of the inverse utility curves in the previous figure (Redrawn from Binford (1978: :81, Fig. 2.18). Used with permission of the Lewis R. Binford Estate and Elsevier/Academic Press)

20.2 Early Applications of the Utility Index Approach

In *Bones: Ancient Men and Modern Myths,* Binford (1981) used utility curves to analyze archaeological materials from Olduvai Gorge, Bed I. From the relative infrequency of high-utility elements of large mammals in these sites, he inferred that early hominins did not transport choicer carcass parts to consumption locales, but rather took the leavings from carnivore kills and other animal deaths. Analyzing the Klasies River Mouth Cave (1984) archaeofauna, Binford used %MAU:MGUI as one line of evidence to argue that archaic *Homo sapiens*, then the presumed creators of Klasies' Middle Stone Age deposits could only successfully hunt game their own body size or smaller, that they scavenged larger mammal species, which displayed a strong inverse bulk utility curve. Binford's interpretations of the Klasies pattern were later undermined by the association of MSA deposits with modern *Homo sapiens* (Jacobs et al. 2008) and critiques based on collection bias in specimen selection (Turner 1989).

Thomas and Mayer (1983) analyzed a thick deposit of bighorn sheep (*Ovis canadensis*) bones in Gatecliff Shelter in Nevada, using MGUI. They determined that the assemblage displayed an inverse bulk utility curve and inferred that this layer represents a butchery event from which high utility elements had been deleted. Speth (1983) used MGUI values in analyzing the Garnsey bison kill site and found a general inverse bulk utility pattern of representation. He noted that relatively high-utility elements of male bison were taken from the kill, whereas the same elements of female bison were abandoned in place. He proposed that this spring season kill was exploited for marrow by fat-depleted human hunters, with the male bison being in better condition than reproducing females, and thus more attractive to human consumers.

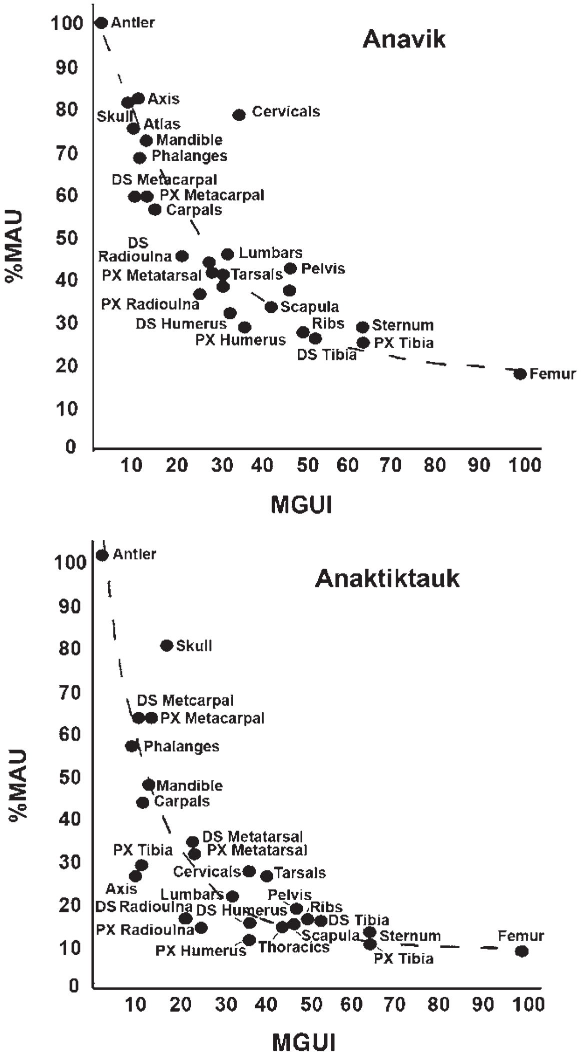

Fig. 20.2 Two examples of inverse utility curves from actual Nunamiut caribou kill-butchery sites, plotted as %MAU against MGUI, with hand-fit curves. Note: Binford originally used the term "MNI" for MAU in his graphics, but later renamed this MAU when it was clear that his mode of calculating this statistic deviated considerably from those for reckoning MNI (Redrawn by the author from Binford (1978: 80, Figs. 2.14, 2.15). Used with permission of the Lewis R. Binford Estate and Elsevier/Academic Press)

20.3 Problems with Calculating and Using Utility Indices and Curves

As zooarchaeologists tried to replicate and apply Binford's utility indices, three problems emerged. The first related to calculating the values, the second pertained to appropriate methods for comparing element frequency patterning statistically, and the third involved the broader question of whether human choice was the main determinant of element frequencies in archaeofaunas. This section addresses the first two issues, and Chap. 21 reviews the third.

20.3.1 Alternate Approaches to Calculating Utilities

Metcalfe and Jones (1988) reported that they could not readily replicate Binford‘s original GUI calculations using his published data and suggested a simpler method of reckoning the index. Noting that Binford‘s original calculations for the Meat Utility Index (MUI) were quite complicated, they proposed that a similar result could be produced by the following calculation:

$$\text{MUI} = \text{gross weight of part} - \text{dry bone weight of part}$$

The “gross weight of a part” is that of a fully fleshed element or body segment, including all marrow, grease, fat, and meat, so MUI lumps total meat, fat, marrow, and grease weights in the calculation. Metcalfe and Jones noted that it is probably not worthwhile to separate the MUI from the grease utility index (GUI) since, in their analysis, the correlation coefficient of MUI to GUI is 1.00. They argued that this simplified approach permits a more straightforward calculation of nutritional value than Binford’s approach, which may in turn encourage researchers to construct indices for taxa with substantially different anatomy from the two that Binford analyzed. Metcalfe and Jones went on to propose the “food utility index” (FUI), in which low-utility “riders” are handled with the same averaging approach applied by Binford in creating the MGUI (Table 20.1). Metcalfe and Jones (1988:496) noted that some of Binford‘s original analytic units for MGUI were not realistic in many situations, asserting that whole-long bone values, rather than Binford’s proximal and distal values, are more broadly useful, for cases in which butchers dismember carcasses by cutting through joints, as do Nunamiut people with warm-weather kills. Food utility indices have been derived for other economically important species. (e.g. O'Brien and Liebert 2014; Rowley-Conwy et al. 2002)

Metcalfe and Jones also challenged Speth‘s assertion that relative fat level is the only utility-related variable that could account for the Garnsey assemblage. They argued that the sex-biased selectivity reflected in the archaeofauna could simply stem from the considerable sexual dimorphism between male and female bison: any body segment of a male, they argue, would yield more of all nutrients than would the same part of females. “We suspect that much, if not all, of the variation noted by Speth in the selection of body parts would be accounted for simply as a function of their different FUI values” (Metcalfe and Jones 1988:500).

In their 1988 article, Metcalfe and Jones did not discuss whether marrow utilities could sometimes usefully be treated as a separate variable rather than as a component of the FUI. By definition, seasonal variations between sexes in FUI values for a given element would incorporate fluctuating fat (and white marrow) levels. However, in another article the same year (Jones & Metcalfe 1988), they outlined their difficulties in replicating Binford’s (1978) marrow utility index, which was based upon a calculation from three variables: an element’s actual marrow cavity volume; fat quality, with a positive weighting for the proportion of oleic acid, and processing time. Working with Binford's own data (1978:24, 30) on Nunamiut selection of skeletal elements to prepare *akutuk*, a marrow-based delicacy, they reported the strongest correlation ($r = 0.97$) with a single variable, marrow cavity volume. They reported a much weaker, negative relationship ($r = -0.53$) between oleic acid content and Nunamiut selectivity of skeletal elements as reported by Binford and therefore dismiss fatty acid content as a predictor of selectivity. They recommended empirically deriving and using this value for species studied, as a proxy for the volume of marrow available in any given element, for any assessments of relative marrow value. Foreshadowing the approach taken by Lupo (2006; Chap. 19), Jones and Metcalfe recommended taking a return rate approach to marrow indices, assessing each elements' marrow yields in light of the processing times involved in retrieving the marrow from it. Using Binford's data, they offered such return rates for caribou elements (Jones & Metcalfe 1988: 421, Table 3, Fig. 3).

Morin (2007) reviewed ethnographic, zooarchaeological, and physiological research and offered new insights on the underlying aspects of marrow bone selectivity discussed by Binford and Jones and Metcalf. Returning to the relationship of specific fatty acid content to human selectivity, Morin reported that marrow of ungulates' limb extremities is proportionately higher in unsaturated fatty acids, including oleic and palmitoleic acids (Fig. 20.3). This marrow is softer and considered more palatable by an array of ethnographic informants in various studies. In reviewing Binford's *akutuk* study and Metcalfe and Jones's critique of it, Morin noted that the respective researchers were not assessing the same variables. Binford was assessing Nunamiut *selectivity* for *akutuk* preparation, relative to a specific set of previously stockpiled marrowbones. By contrast, because their aim was to develop a method widely applicable to archaeological cases, in which the original pool from which elements were selected is unknown, Metcalfe and Jones were assessing the *rank order* (expressed as %MAU) of elements selected, without reference to the original stock. Morin found that upper leg elements of fore and hind legs, with lower proportions of unsaturated fatty acids, were less frequently selected for *akutuk* (Fig. 20.3). He states, "Although the proportions of skeletal parts selected for marrow procurement are strongly correlated with marrow quantity, a stronger correlation was found with quantity of unsaturated fatty acids" (Morin 2007: 69). This contradicts Metcalfe and Jones's inference that specific fatty acid content bears little relation to human choice of elements.

Based on his analyses, Morin proposed a new scale of marrow utility, the Unsaturated Marrow Index, to more accurately calibrate the relative nutritional values of different marrow-bearing long bones. Given the importance of EFA's in supporting brain and neural development during pre-and post-natal human development (Chap. 5), this later research supports application of some form of a marrow utility assessment in assemblage analysis.

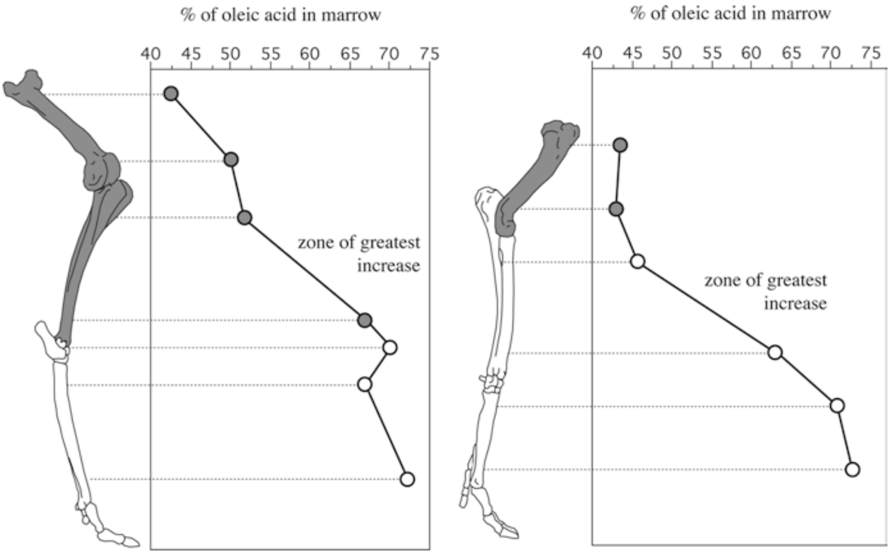

Fig. 20.3 Diagrammatic representation of increases in oleic acid in hind leg (left) and foreleg (right) of caribou, showing higher incidence in distal long bones and zones of greatest gain in oleic acid for each limb set (From Morin 2007:75, Fig. 7, used with permission of E. Morin and Elsevier)

20.3.2 Other Studies Calibrating Nutritional Utility

The phylogenetic history and functional anatomy of large land and marine mammals is diverse, and zooarchaeologists have undertaken economic anatomy studies of a number of species to better understand the constitution of archaeofaunas on several continents. While not using precisely the methods of Binford or Jones and Metcalfe, Blumenschine and Madrigal (1993) reported on variations in marrow yields in eight species of African antelope, wild pig, and equid. Blumenschine and Caro described flesh yields of Thomson's (*Eudorcas thomsonii*) and Grant's (*Nanger granti*) gazelles, impala, and wildebeest (1986). Bar-Oz and Munro (2007) assessed marrow yields in mountain gazelle (*Gazella gazella*) in the Levant. Emerson (1990) derived utility indices for bison. Madrigal (2004) calculated utility indices for North American white-tailed deer (*Odocoileus virginianus*), while Belardi and Gómez Otero (1998) did so for the huemúl (*Hippocamelus bisulcus*), a South American deer. Argentinean archaeologists have derived meat utility indices for the wild South American camelid, the guanaco, *Lama guanicoe* (Borrero 1990), and for its marrow (Mengoni Goñalons 1996). Outram and Rowley-Conwy (1998) derived meat and marrow indices for equids. Two studies have specified the meat utility of phocid, or earless, seals (Diab 1998; Lyman et al. 1992), and one has described utility indices for otariid, or eared seals (Savelle et al. 1996). Savelle and Friesen (1996) derived a meat utility index for small- to medium-sizes toothed cetaceans such as dolphins (Delphinidae) and porpoises (Phocoenidae).

Savelle (1997) presented a thoughtful consideration on the architectural utility of cetacean skeletal elements in northern areas with a dearth of wood construction materials. He argued that bones of architectural potential, the cranium, mandible, maxilla/premaxilla, and cervical vertebrae, all have relatively low meat utilities but display high "architectural utility" at prehistoric Thule sites in the Arctic.

20.3.3 *Drying Utility: Another Significant Index in Mass-Kill or Distant Transport Situations*

Many foragers, whether engaging in mass-kill acquisition of large prey or serial predation on individual animals, dry meat to extend its "shelf-life" and to reduce its weight for transport, as do food-producing people in other situations. Friesen (2001), like Binford, analyzed sites reflecting Inuit caribou butchery and caching, and he revived a discussion of selectivity and transport and/or caching based upon various body segments' potential to produce dried meat for long-term storage. Binford (1978) had introduced the Drying Utility Index, using a rather complex formula that took into account the associated amount of meat of a skeletal element, as well as the potential of brain and marrow to cause meat spoilage. The derivation of the index incorporated the finite amount of meat associated with an element, the ratio of bone weight to gross weight, and the presence of brain or marrow in the associated element. Friesen (2001:319) rephrased the ideal body portion for drying as having, "a great quantity of meat attached, a high bone-to-gross-weight ratio, and no brain or marrow."

Much as Jones and Metcalfe simplified the MGUI to the FUI, Friesen (2001:319) rewrote the derivation of meat drying utility using simpler terms than those of Binford to derive a Meat Drying Index (MDI):

$$\frac{(\text{meat wt})(\text{bone wt})}{(\text{gross wt})(\%\text{brain marrow wt})}$$

Friesen's tabulation of MDI for caribou, based upon Binford's data, shows that the skeletal elements of the thorax (thoracic vertebrae, ribs, sternum), adjacent axial regions (cervicals, lumbars), and pelvic bones have the highest values, with ribs having more than two times the MDI of thoracic vertebrae (Table 20.2). Reworking Binford's data and that from three Barren Ground Inuit caches he excavated, Friesen argued that assessing element frequencies using the MDI has significant relevance for revealing preservational decisions in the field and in specific caches. However, he cautions that, especially at long-term encampments, the aggregate situational considerations and decisions involved in animal processing may obscure the "pure" patterns emerging from meat-drying choices.

De Nigris and Mengoni Goñalons (2005) applied Friesen's drying utility indices to central-west Patagonian sites spanning much of the Holocene, using actualisti-

Table 20.2 Friesen's (2001: 320, Table 2) adaptation of Binford's (1978) Meat Drying index (MDI). Shaded area shows highest-ranking elements for meat drying

Element	Gross Weight	Bone Weight	Brain or Marrow Weight	% Brain or Marrow Weight	Meat Weight	Meat Drying Index
Skull	1397.1	460.1	361.8	100.0	575.2	1.9
Mandible w/ tongue	1778.1	178.1	8.7	2.4	1591.3	66.4
Mandible w/out tongue	768.1	178.1	8.7	2.4	581.3	56.2
Atlas-axis	630.2	106.0	0	1.0	524.2	88.2
Cervical 2-7	2112.2	207.0	0	1.0	1905.2	186.7
Thoracic	2789.6	357.0	0	1.0	2432.6	311.3
Lumbar	1940.0	234.0	0	1.0	1706.0	205.8
Pelvis	3175.2	644.2	9.5	2.6	2521.5	196.8
Rib	3687.4	1037.0	0	1.0	2650.4	745.4
Sternum	3628.8	207.0	0	1.0	3421.8	195.2
Scapula	2398.4	103.0	4.0	1.1	2291.4	89.5
Humerus	1661.3	174.9	30.0	8.3	1456.4	18.5
Radius	918.5	164.0	28.4	7.9	726.1	16.4
Metacarpal	374.2	106.2	16.6	4.6	251.4	15.5
Femur	5342.3	202.9	41.1	11.4	5098.3	17.0
Tibia	1532.0	222.1	50.6	14.0	1259.3	13.0
Metatarsal	754.1	173.1	40.3	11.1	540.7	11.2
Phalanx	294.8	108.0	3.2	1.0	183.6	67.3

cally derived utility indices for the guanaco (Mengoni Goñalons 1996), the main mammal prey in the region. They derived a MDI for guanaco using Friesen's formula. Their use of these indices was aimed at better accounting for a pattern observed in cave and shelter assemblages in their study region, which displayed either no selective transport of body segments or a predominance of long bones and a lack of axial elements. In the study area, it is likely that animals were taken one-by-one, or in small numbers, rather than as mass kills, in a cold and dry landscape. One better-preserved archaeofauna had moderate to strong correlations of element frequencies to meat and marrow utilities, respectively. De Nigris and Mengoni Goñalons (2005) infer that this sample represents a locale for preferential processing and consumption of bones rich in meat and marrow and with low bone-to-meat proportions. They further proposed that this assemblage structure represents the starting point of a sequential chain of selective processing, transport, and consumption, with marrow-bearing long bones being processed and discarded first. De Nigris and Mengoni Goñalons do not explicitly state why these elements were processed earliest, but harking to discussions by Lupo (2006) and Emerson (1993) in Chap. 19 and Binford and Morin in this chapter, marrow must be consumed before it turns rancid – and discard of meat-stripped log bones reduces transport costs.

De Nigris and Mengoni Goñalons (2005:163) report that all assemblages displayed a significant *negative* correlation of element frequencies with MDI, implying that those bone units more suitable for drying were preferentially removed from acquisition locales to other places where they were processed for jerky. They infer, "Bones that are rich in meat only, and have a high bone to meat proportion were preferentially consumed later due to their suitability for drying" (2005:164). Thus, the authors are, without graphically depicting it as such, describing much the same spatiotemporal segregation of handling and consumption events as described in the *chaîne opératoire* approach advocated in Chap. 15. De Nigris and Mengoni Goñalons stress that the signature of selective transport for drying does not necessarily imply long-term storage. Rather, immediate consumption of marrow and meat, and short-term preservation of some meat from the same animal, "might have allowed inland Patagonian hunter-gatherers to cope with irregularities in the intake of energy such as nutritional stress related to the seasonal depletion of animal fat, and other temporal incongruencies" (2005:164).

20.4 Statistical Problems with Utility Curves

The x-y axis plots of %MAU to utility indices – especially Binford's curves fitted to the distribution of data points – suggest that parametric statistical analysis, e.g. Pearson's correlation coefficient or regression analyses (Siegel and Castellan 1988) might be appropriate (Chap. 18). Despite being expressed as ratios of 100, utility indices are not ratio scale variables that can be multiplied or divided into one another, and the intervals between them are irregular. They ordinal scale variables, which can be arranged from highest to lowest and vice-versa. Hence, they so they are not amenable to parametric statistical tests. Working with these values, Lyman (1985) and Grayson (1989) instead applied nonparametric rank-order tests appropriate to such ranked data, namely Spearman's rho or Kendall's tau. Fundamentally, these tests ask how well one variable, in this case a utility index (MGUI or FUI), predicts the frequency rankings of skeletal elements in a sample.

20.4.1 Are Utility Curves Actually Useful?

Binford hand-fit curves into distributions of %MAU in his Nunamiut data (Fig. 20.2), and others, such as Thomas and Mayer, also attributed the Inverse Bulk Utility strategy to a curve by inspection rather than through a statistical process. The Inverse (sometimes called Reverse) Utility Curve has been the focus of debate about its causes, as will be seen later in this chapter. Though critical of Binford's inference of human selectivity from this curve and advocating consideration of the bone mineral determinants of element, Lyman (1985, 1992) displayed data in the same manner. But, given that they cannot be subject to regression analyses, are such curves actually analytically useful?

I have found it helpful to start thinking through such published utility distributions by visualizing the natural distribution of skeletal MGUI or FUI values in the species under study. Each carcass offers an array of utility values upon which human decisions act, one carcass at a time, whether the handlers are processing a single animal or multiple animals acquired in a mass-kill. Iterative choices, acting on multiple carcasses with this array, create the curves discussed in the zooarchaeological literature, whether abstract or based on concrete archaeofaunal and ethnographic data.

Figure 20.4 shows this pattern for caribou (Binford 1978:74, Table 2.7) using "% of Skeleton" rather than %MGUI on the y-axis; base data for the graphic are in Table 20.1. A few points are apparent. First, most high-utility elements occur at frequencies of two per carcass, e.g. the femora, patellae as riders, and tibiae. Second, to create a high-utility array such as that modeled by Binford for the Gourmet Utility Curve (Fig. 20.1), with the majority of elements of MGUI greater than 50, many reiterated selections of such relatively rare elements must be made from multiple carcasses, all in the same high-utility mode. This level of selectivity is unlikely to be a realistic assemblage outcome. From Binford's account (1978: 60–61) of specific incidents in Johnny Rulland's acquisition of caribou and moose, it is possible that a single hunter can situationally adopt a gourmet strategy when encountering a large prey animal at a distance from a camp or longer-term residential base. The hunter butchered the animal competently but carried back to the base only the highest-ranked limbs, plus internal organs requiring immediate consumption. There, after a meal, the hunter could expect to recruit a carrying party to retrieve the rest of the kill, whereupon a bulk utility pattern transport is established. One such moose recovery was frustrated by an unexpected, nine-day snowfall, in which case the gourmet strategy held but would not have, had the carrying party not been stranded at camp by the blizzard, while the moose was buried under several feet of snow.

The classic Bulk Utility Curve model (Fig. 20.1) requires selecting differentially more elements in the MGUI 50–100 range. Of these, the 26 ribs, at MGUI 50 and constituting 19% of entire skeleton, would be the preponderant element (Table 20.2) but higher-ranked elements, constituting only 6% of the individual skeleton, would offer far fewer selection options on a carcass-by-carcass basis than predicted by the model. It may be unrealistic, even with mass kill processing, to expect that people would be so selective as to build such an assemblage at the end-point of transport, even mass kill situations.

However, one ethnographic case, so specific and localized that similar sites are unlikely to be found in most regions, shows such a curve. Caribou body units were introduced in 1971 and 1972 into Nunamiut ice cellars, large pits cut into a permanent, subterranean ice dome for frozen meat storage (Binford 1978: 127–129, Figs. 3.21, 3.22). Compared with kill-butchery sites from the same years, the utility distributions are not mirror images of those localities: they were biased differently each year by decisions by women of Anaktuvuk village made to include or exclude specific cuts of meat in the ice cellar, according to the overall fortunes of the spring hunting season. This process included discard outside the ice cellar of parts deemed to be from animals of poor condition, situationally broader inclusion of moderate utility parts in a year of poor hunting yields, and preferential transport from the

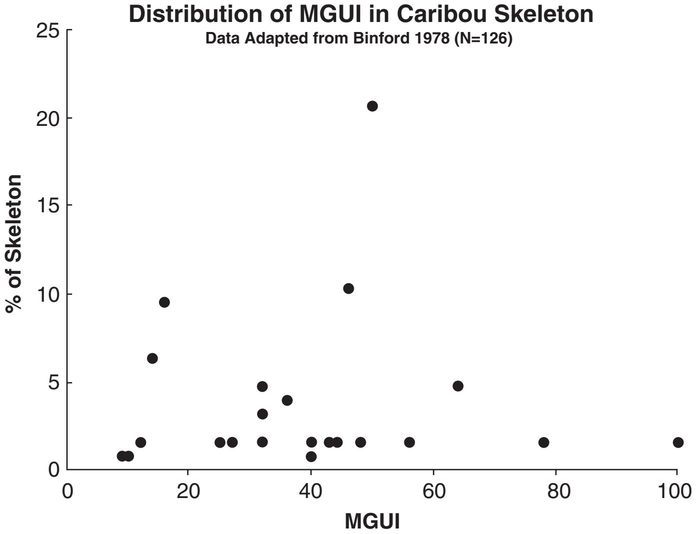

Fig. 20.4 Distribution of Modified General Utility Index values in a caribou skeleton. To convey the rates of occurrence of various elements with different MGUI values, the y-axis shows percent frequency of an element and its associated value in the caribou skeleton, rather than %MGUI, which also norms for these same element counts. Note: Binford used proximal and distal values for long bones, which inflates the contribution of long bones. To coincide more with ethnoarchaeological observations that butchers most often handle whole long bones, Binford's proximal and distal values are averaged and only one value per long bone is presented (Figure by the author, using Binford's 1978 MGUI data, see Table 19.1)

processing site to the main village of high-ranked skeletal segments. Such special storage facilities, at a distance from a village, simply due to the accident of nature that produced an ice deposit in the permafrost, thus reflect a double winnowing of mass kills, driven by considerations both of spoilage and of assessment of potential nutritional need in the season ahead. The example also points out the importance of "home base" management decisions on the constitution of specific deposits of skeletal elements.

The two inverse utility curves merit consideration, but perhaps for somewhat different reasons. The Inverse Gourmet Utility curve is unlikely to be realistic for reasons outlined above regarding the Gourmet Utility curve itself. The Inverse Bulk Utility curve has been the subject of much discussion about the influence of differential durability of different skeletal elements, to be taken up in detail in Chap. 21.

As noted by (Lupo 2001), residential assemblages as a whole reflect an average of varied situational decisions taken over the duration of use of site, in which even the same species are handled differently, due to the circumstances of acquisition and the varying needs of personnel at the home base. Binford (1978: 114–115) discussed the variations in causal factors that produced very different additions over three observed years of selective transport to the same locale, the winter village of Anaktuvuk. He never summarized the totality of utility signatures from the site.

However, if one were to sample skeletal elements across dog yard, meat rack, household, and bone grease assemblages mentioned in Binford, one receives the impression that this long-term, seasonal residential camp is not the simple inverse of kill-primary butchery localities.

Before leaving the role of nutritional utility in structuring assemblage composition, it is worth reiterating that modern caribou hunters such as the Nunamiut, from which many recent discussions of transport factors stemmed, are not typical of most hunters documented by ethnographic and historic records. In mass kills, an efficiency-driven system of body segment triage emerges: some are definitely marked for discard, others for transport, and yet others are transported or discarded according to situational factors. However, most large prey acquisition is one animal at a time, discussed by Emerson (1993) who analyzed transport under mass versus single acquisition, and others mentioned in Chap. 19. Analysts should certainly know enough about the habits of prey species encountered in archaeofaunas to grasp the range of encounter situations hunters might face with them – whether they are come upon singly or in groups –and reflect on how this will affect transport decisions.

20.4.2 Nutritional Utility or Return Rate?

As foreshadowed in Chap. 19's discussion of Hadza transport decisions and in citations in this chapter, a related measure of relative nutritional value of vertebrate body segments is available: the return rate. Return rates are widely used in behavioral ecological analysis in zoology because they provide a more realistic assessment of the trade-offs that specific resources offer foraging animals (Krebs and Davies 1993). Return rate refers to the net income, rather than the gross value, of a resource, in which the average costs of locating and processing the resource are deducted from the resource's absolute value. In behavioral ecology, the income is normally calibrated in kilocalories, while for reasons of practical expediency, the costs are usually calibrated in time as a proxy for energy expended (Chap. 24). The base assumption is that, the greater the time expended, the more calories are spent as well. Two classic classifications of time invested in obtaining a resource are deducted from the net energy yield of the resource: search time and handling time.

In most applications of return rates to species other than humans, species or taxonomic groups are ranked as food resources in terms of net caloric returns (Barlow and Metcalfe 1996; Bettinger et al. 1997). This is a logical outgrowth of patch choice theory, which will be described in more detail in Chap. 24. For human foragers using animal prey, the matter is more complicated because costs of search and handling often involve effort invested in developing infrastructure and gear that obtain, dispatch, and process prey, as again will be discussed in Chap. 24.

20.4.3 Questions about the Primacy of Human Selectivity in Structuring Archaeofaunas

Almost simultaneously with publication of utility index approaches, other researchers questioned inferences from them. Foremost among the reservations expressed was whether other taphonomic processes could produce skeletal element representation attributed by Binford and others to human selectivity. This question is a variant of the longstanding paleontological question of whether fossil vertebrate element frequencies that depart from those typical of the skeleton were produced by fluvial transport or in-place destruction by taphonomic processes. Chapter 21 takes up this topic in detail.

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Chapter 21
Calibrating Bone Durability

While some zooarchaeologists worked to standardize the nutritional values of tissues associated with various skeletal elements, others raised a second, intersecting issue: the role of differential element durability in determining element frequencies in archaeofaunal assemblages. The paleontological taphonomic literature has long distinguished two types of postmortem processes that produce element frequencies in fossil accumulations: transport of elements away from or to a sample locale, on the one hand and *in situ*, or in-place, destruction of elements at the locality, on the other Guthrie (1967; Lawrence 1968; Olson 1971). Paleontologists also recognized that skeletal elements vary in their construction and their densities of bone tissue and, therefore, in their potential for surviving postmortem taphonomic processes. Awareness of this literature led some zooarchaeologists to question whether archaeofaunal element frequencies were caused solely by human selective transport or whether durability-dependent deletion of more delicate skeletal elements could also affect them. This chapter reviews zooarchaeologists' attempts to calibrate density-dependent bone attrition, and to assess how this relates to the effects of human selectivity.

In zooarchaeology, the potentially equifinal results of human selectivity and differential bone survival have generated a profusion of studies and controversies. This literature is complicated in several ways. First, many such discussions implicate multiple, variable, and often-unarticulated base assumptions about how to link actualistic research to archaeofaunal case analyses. Second, some methodological discussions concerning bone tissue density are offered in the context of arguments over methods of quantification; these are indeed related topics, but teasing out the strands of one from the other is challenging. Third, these discussions are often entangled with competing claims regarding early hominin behavior, with which the average zooarchaeological reader may neither be thoroughly acquainted nor deeply concerned. All participants in these sometimes heated debates believe they are doing good science, the logic of opposed lines of argument is close to impeccable, and it only becomes more so with time – but the same is true for many theological positions. The reader interested in how best to assess *in situ* destruction cannot be faulted for becoming dazed around the thirtieth article.

D. Gifford-Gonzalez, *An Introduction to Zooarchaeology*,
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The first part of this chapter aims to sort through basic themes in research on bone durability in zooarchaeology since the 1980s, abstracting them from the topically based arguments in which many are embedded. It accepts *a priori* that element frequencies should be seen as potentially subject to equifinality: like stone striations on bone surfaces, multiple processes and actors can caused them. Moreover, some authors remind us that element frequencies are abstracted statistics based upon NISP and that the chain of analytic procedures can, if care is not taken, determine the final pattern of the aggregate data (Rogers 2000). The second part of this chapter examines quantitative issues associated with element survival in more detail.

21.1 Fundamental Questions in Durability-Related Survival of Skeletal Elements

It is useful to outline relevant, intersecting issues relating to skeletal element durability in the form of questions, to be discussed in this section of the chapter.

1. Do various skeletal elements have different amounts of bone tissue per unit volume?
2. Can this variability be calibrated with a degree of replicability?
   (a) What factors can throw off estimates? Can they be corrected for?
   (b) What method is currently most accurate in estimating bone mineral density? Why?
3. Does a negative correlation exist between nutritional utility and bone durability? That is, are the skeletal elements most likely to be selected for transport also the most fragile and vulnerable to destruction?
4. What causes destruction of more fragile elements or portions of elements?
   (a) Can we tell which actor or other taphonomic process is involved?
5. How can we apply knowledge of bone durability to archaeofaunal analysis?
   (a) How can one distinguish *in situ* destruction from selective transport?
   (b) How can one best assess skeletal element representation?

The next subsections take these topics in turn, reviewing zooarchaeological research on the role of bone durability as a structuring factor in producing archaeofaunal element frequencies. It reviews the basic analytical methods developed to assess and compare density-dependent bone destruction, with some key references to the current state of knowledge and opinion. Recall that this chapter, like Chap. 20, focuses on *aggregate patterning* of element frequencies. These are believed to shed light on recurrent patterns of human behavior or its social and ecological contexts, as represented by the nested boxes for levels of inference introduced in Chap. 3. The continued relevance of drawing upon actor/effector evidence to assist in skeletal elements will be stressed.

21.1.1 Do Skeletal Elements Differ in Their Amounts of Bone Tissue per Unit Volume?

A casual observer handling a disarticulated skeleton laid out on a tabletop intuitively grasps that not all skeletal parts contain the same amount of bone tissue in relation to their overall size. The sternum and sacrum are very light, being composed nearly entirely of cancellous tissue with a thin veneer of cortical bone, while carpals and tarsals are much heavier due to their much denser compact bone tissue. As was the case with bone fracture patterns, properties inherent to the elements themselves, rather than the modifying actors, can strongly influence element survival in the face of destructive processes, and thereby structure element frequencies. Human selectivity may produce the initial element frequencies in an assemblage, but actualistic research in paleontology and zooarchaeology has shown that subsequent mechanical or chemical forces can modify these original frequencies according to different elements' intrinsic properties, including their surface area in relation to their volume, as it did with weathering and the amount of bone tissue per unit volume.

21.1.2 Can this Variability be Measured with a Degree of Replicability?

As part of his palaeoanthropological research on differential skeletal element survival (Chap. 2), Brain (see 1981 for an overview) measured modern goat elements' specific gravity, using the time-honored water-displacement method. He noted that the differences in modern element survival rates when subjected to carnivore gnawing or ungulate trampling correlated well with this measure. Behrensmeyer (1975) also recorded observations on the specific gravities of skeletal elements from modern taxa analogous to those found in fossil deposits in the Lake Turkana basin. Binford and Bertram (1977) attempted to extend Brain's use of specific gravity to their study of skeletal element destruction by Alaskan working dogs and wolves, but found the method wanting as a readily replicable process. Thus, by the early 1980s, paleontologists and zooarchaeologists were increasingly concerned with how best to distinguish selective transport of body segments from differential destruction by various agents, especially carnivores. Some sought more readily replicated methods for assessing the bone tissue density of various skeletal elements.

Lyman (1984) observed that mammalian bone *tissue* has a single specific gravity and physical density, but that individual *skeletal elements*, with their differing combinations of compact and cancellous tissue, as well as their internal voids for marrow, comprise *variable volumes* of such tissue, with different resulting "volume densities." Lyman (1984: Table 1) reviewed previous specific gravity studies, observing a wide variation in values produced for similar elements. He argued that variations in the bone tissue composition of skeletal elements, and hence their survival potentials, seriously complicate inferences about human behavior from archaeofaunal element frequencies and Binford's utility indices.

Lyman (1984) introduced a new level of replicability in estimating bone tissue density with the application of biomedical scanning equipment, specifically single-beam photon densitometry, to measure bone tissue in skeletal elements. At that time, photon absorptiometry was widely applied in measuring the bone tissue in patients at risk of osteoporosis, based on a representative element, usually the distal radius and ulna of the forearm. The single photon ("X-ray") beam moves over a plate on which the scanned tissue rests. A detector on the plate registers the beam, with the tissue of the scanned tissue partially impeding the beam.

Because the photo beam sensor registers a two-dimensional scan line across the element, the volume of the bone tissue in a three-dimensional element must be estimated with a formula that converts the photon-derived reading into a three-dimensional figure. Lyman originally estimated bone volume at each scan site as the product of the beam scan's width (1/8 in.), the maximum bone length, and the maximum bone thickness. Later, he used an average bone thickness (Lyman et al. 1992). The method treats all skeletal elements as cross-sectionally rectangular at the scan site and assumes that the element is a solid, lacking medullary or inter-trabecular spaces. These assumptions may not be warranted, as will be seen below. Nonetheless, Lyman's scan-site approach has guided later research and development on this topic.

Lyman initially called the resultant measure of bone tissue in three dimensions "bulk density," which he defined as, "the ratio of the weight of a volume of a substance to the volume of that substance including the pore space volume" (1985: 226). Thus, the statistic should reflect the degree to which an element is tightly packed with bone tissue. By this criterion, vertebrae have low bulk density, and carpal and tarsal bones have very high bulk density. Later, Lyman (e.g. 1992) changed to the term "volume density" (VD) as the more accurate name for the same index.

Lyman (1984) scanned multiple sites (Fig. 21.1) on axial and appendicular skeletal elements of 13 deer (*Odocoileus virginianus* and *O. hemionus*), plus a sheep (*Ovis aries*) and pronghorn antelope *Antilocapra americana*. He targeted scans to locations of Binford's MGUI values, such as the proximal and distal femur, adding long bone shafts, for which Binford had not assigned MGUI. He also made multiple scans for elements treated in aggregate by Binford, for example vertebral regions, ribs, carpals, and tarsals, but later averaged these values to compare with the MGUI. For any element to which Binford had given distinct (e.g. proximal and distal) MGUI values, he retained distinct values (Table 21.1).

Over the next decade, a variety of VD estimation studies, using either single-beam photon or Dual-energy X-ray Absorptiometry (DEXA) scans, were made with skeletal elements of other taxa. These included the marmot *Marmota marmota* (Lyman et al. 1992), the leporids: domestic rabbit *Oryctolagus cuniculus*, eastern cottontail *Sylvilagus floridanus*, arctic hare *Lepus canadensis*, black-tailed jackrabbit *Lepus californicus* (Pavao and Stahl 1999), the bison *Bison bison* (Kreutzer 1992), the South American camelids: guanaco *Lama guancoe*, vicuña *Lama*

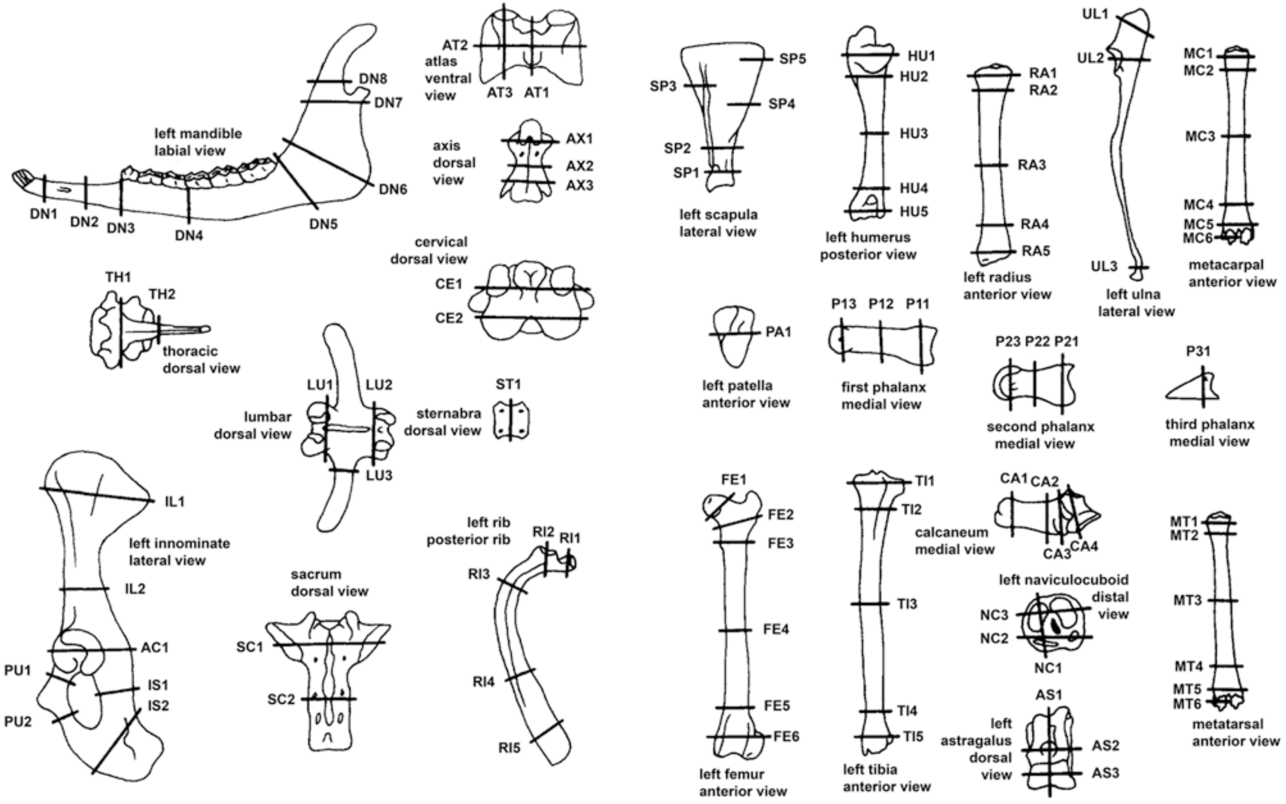

Fig. 21.1 Lyman's scan sites (Lyman 1985: 274–275, Fig. 2), also used as the basis for CTscan sites by Lam et al. (1998, 1999). (Redrawn by the author, used with permission of R. L. Lyman and Elsevier)

Table 21.1 Summary of Lyman's (1985) scan sites for deer skeletal elements, with Volume Density (VD) values, and Lam et al.'s (1998) caribou CTScan Bone Mineral Density (BMD) values, according to their BMD1 and BMD2 calculations (see text for details)

	N	Lyman (1985) deer VD	Lam et al. (1998) Caribou CTScan	
Element			BMD_1	BMD_2
Cranium (petrosal)	1	N/S		1.29
Mandible	2			
DN1		0.55	0.65	
DN2		0.57	0.75	1.05
DN3		0.55	0.63	1.07
DN4		0.57	0.67	1.06
DN5		0.57	0.56	1.05
DN6		0.31	0.66	**0.84**
DN7		0.36	0.98	1.01
DN8		0.61	0.99	
Atlas	1			
AT1		0.13	0.47	
AT2		0.15	0.42	
AT3		0.26	0.49	
Axis	1			
AX1		0.16	0.62	
AX2		0.10	0.42	
AX3		0.16	0.42	
Cervical	5			
CE1		0.19	0.45	
CE2		0.15	0.43	
Thoracic	13			
TH1		0.24	0.38	
TH2		0.27	0.53	
Lumbar	6			
LU1		0.29	0.49	
LU2		0.30	0.45	
LU3		0.29	0.51	
Sacrum	1			
SC1		0.19	0.37	
SC2		0.16	0.40	
Innominate	2			
IL1		0.20	0.43	
IL2		0.49	0.70	1.02
AC1		0.27	0.64	
PU1		0.46	0.58	
PU2		0.24	0.54	
IS1		0.41	0.67	0.94

(continued)

Table 21.1 (continued)

Element	*N*	Lyman (1985) deer VD	Lam et al. (1998) Caribou CTScan	
			BMD_1	BMD_2
IS2		0.16	0.30	
Rib	26			
RI1		0.26	0.47	
RI2		0.25	0.49	
RI3		0.40	0.62	0.96
RI4		0.24	0.65	0.94
RI5		0.14	0.40	0.40
Sternum	6			
ST1		0.22	N/S	
Scapula	2			
SP1		0.36	0.66	1.01
SP2		0.49	0.73	1.04
SP3		0.23	0.73	
SP4		0.34	0.69	1.01
SP5		0.28	0.48	
P Humerus	2			
HU1		0.24	0.26	
HU2		0.25	0.31	**0.44**
Sh Humerus				
HU3		0.53	0.61	1.12
D Humerus				
HU4		0.63	0.62	1.08
HU5		0.39	0.48	
P Radius	2			
RA1		0.42	0.53	
RA2		0.62	0.57	1.08
Sh Radius				
RA3		0.68	0.73	1.09
D Radius	2			
RA4		0.38	0.38	0.97
RA5		0.43	0.49	
P Ulna	2			
UL1		0.30	0.49	
UL2		0.45	68	**0.84**
D Ulna	2			
UL3		0.44	NS	NS
P Metacarpal	2			
MC1		0.56	0.63	*0.92*
MC2		0.69	0.69	1.08
Sh Metacarpal				

(continued)

Table 21.1 (continued)

Element	*N*	Lyman (1985) deer VD	Lam et al. (1998) Caribou CTScan	
			BMD$_1$	BMD$_2$
MC3		0.72	0.79	1.10
D Metacarpal	2			
MC4		0.58	*0.59*	*1.01*
MC5		0.49	0.48	
MC6		51	0.68	
P Femur	2			
FE1		0.41	0.39	
FE2		0.36	0.35	**. 52**
FE3		0.33	0.35	**0.74**
Sh Femur				
FE4		0.57	0.57	1.15
D Femur				
FE5		0.37	**0.40**	**0.61**
FE6		0.28	0.32	
FE7		N/S	0.30	
Patella	2			
PA1		0.31	0.57	
P Tibia	2			
TI1		0.30	0.35	
TI2		0.32	*0.44*	*1.01*
Sh Tibia				
TI3		0.74	0.71	1.13
D Tibia	2			
TI4		0.51	0.53	1.12
TI5		0.50	0.39	*0.73*
Fibular	2	0.52	0.68	
Naviculocuboid	2			
NC1		0.39	0.56	
NC2		0.33	0.62	
NC3		0.62	0.55	
Astragalus	2			
AS1		0.47	0.68	
AS2		0.59	0.70	
AS3		0.61	0.63	
Calcaneus	2			
CA1		0.41	0.52	
CA2		0.64	0.80	*0.94*
CA3		0.57	0.66	
CA4		0.33	0.73	
P Metatarsal				

(continued)

Table 21.1 (continued)

Element	*N*	Lyman (1985) deer VD	Lam et al. (1998) Caribou CTScan	
			BMD_1	BMD_2
MR1		0.55	0.58	*0.90*
MR2		0.65	0.57	1.10
Sh Metatarsal				
MR3		0.74	0.65	1.08
D Metatarsal	2			
MR4		0.57	0.54	1.08
MR5		0.46	0.41	
MR6		0.50	0.59	
Phalanx 1	8		0.56	
P11		0.36	0.48	
P12		0.42	0.56	*0.92*
P13		0.57	0.71	
Phalanx 2	8			
P21		0.28	0.49	*0.61*
P22		0.25	0.64	*0.72*
P23		0.35	NS	
Phalanx 3	8			
P31		0.25	0.48	
Carpals	10			
Scaphoid	2	0.98	0.70	
Lunate	2	0.83	0.67	
Cuneiform	2	0.72	0.71	
Magnum	2	0.74	0.69	
Unciform	2	0.78	0.72	

vicugna, llama *Lama glama*, and alpaca *Lama pacos* (Elkin 1995; Stahl 1999), domestic cattle *Bos taurus*, domestic sheep *Ovis aries*, farmed European wild boar *Sus scrofa* (Ioannidou 2003), the turkey *Meleagris gallopavo* (Dirrigl 2001), the flightless lesser rhea *Pterocnemia pennata* (Cruz and Elkin 2003), and the North American harbor seal *Phoca vitulina*, with partial skeletons of the harp seal *Phoca groenlandica* included (Chambers in Lyman 1994: Table 7.7).

These findings were applied to assessing bone density-dependent bone destruction in various archaeological cases using rank-order correlation coefficient analysis. Lyman himself (1984, 1985) assessed several archaeofaunas purported to reflect selective transport, such as the Gatecliff Shelter, using volume density figures, as well as extending arguments about the relationship between nutritional utility and bone volume density, which will be treated in a subsequent sections.

21.1.2.1 Factors that Throw off Photon Densitometer Estimates: Bone Shape, Internal Voids

By the early 1990s, several researchers independently noted problems with the derivation of VD estimates in densitometry studies. Two issues emerged: first, the impact of variations in *element shape* on the realism of the VD estimate and second, the failure of the original formula to allow for an element's *internal voids* in the estimate. In a study of human long bone volume density and survival, Galloway et al. (1996) explored how bone *shape* affects photon densitometer-derived VD estimates. They computed three estimates of bone mineral density: (1) the equipment-generated, non-shape-corrected estimate of gm/cm^3, called BMD; (2) Lyman's VD calculation, which divides that density estimate of an element by its thickness; (3) an estimate, which they called BMDc, that attempts to correct for differences in long bone cross-sectional shape by dividing the BMD "by a diameter calculated from the measured circumference" of an element (Galloway et al. 1996: 300), obtained by using a flexible tape to measure the long-bone circumference at a scan site, divided by 3.14 (pi). Using elements of different cross-sectional shapes, they demonstrated that the common VD formula assumptions produce considerable over-estimation of volume density (>125%) in elements with irregular cross-sectional shape. This problem was also recognized and explored by Pavao and Stahl (1999), who advocated VD estimation formulae that take into account the cross-sectional geometry of different leporid elements. See also Lyman's (2014) reworking of these data.

Regarding internal voids, Kreutzer (1992: 283) observed, that, using photon densitometry, there is:

> …no way to account for the size of marrow cavities within long-bone shafts without sectioning the bones and measuring the cavities directly. Ideally, this would be done so that the dimensions of the marrow cavity within each scan site could be eliminated from the calculations of volume.

Kreutzer noted that this measurement is not feasible with museum comparative specimens, and she offers the opinion that both her own and Lyman's VD estimates for long-bone diaphyses are too low by an indeterminable amount. Elkin (1995) actually sectioned guanaco long bones to estimate bone wall BMD, having recognized that internal voids could throw off VD estimates (see also Cruz and Elkin 2003). Elkin (1995) also experimentally established that water-displacement estimates of bone VD produce substantially higher estimates of BMD than those produced by photon densitometry.

Lam and Pearson (2004, 2005) summarized four X-ray scanning technology approaches for estimating bone mineral density, which they classified according to their accuracy. The first were the simple, non-shape-corrected photon densitometer findings, they believe to be the least likely to produce an accurate bone mineral estimate for long bones with medullary cavities or irregularly shaped epiphyseal ends. The second comprise shape-corrected photon densitometer estimates such as those discussed by Galloway et al. (1996), which, however, do not estimate the size of and shape of medullary spaces. These, they say, produce better estimates but still yield values that depart in unpredictable ways from those produced by CTscan (see below), which does visualize internal voids (Lam and Pearson 2005:102, Fig. 1). The third variant, is also based on photon densitometry but also sections bone and uses estimates of medullary cavity size to produce render even more accurate BMD estimates, as did Elkin's 1995 study. Fourth, Lam and Pearson (2004, 2005) contended that X-ray Computed Tomography scanning, commonly known as CTscans, render three-dimensional images of long-bone medullary cavities and cancellous bone tissue, using algorithms to calculate the three-dimensional bone mineral volume of an element. Lam and Pearson argue that CTscans produce the most accurate estimate of the bone mineral density.

21.1.2.2 Most Accurate Estimator of Bone Mineral Density: X-Ray Computed Tomography

Over several years, Lam and colleagues extensively explored the sources of error in photon densitometry estimates outlined above and developed CTscan applications to zooarchaeology (Lam et al. 1998, 1999, 2003; Lam and Pearson 2004, 2005). Computed Tomography scanning is used in medicine to produce three-dimensional images of soft and hard internal tissues of the body. The technique resembles photon densitometry in that an X-ray beam passes through a body or body segment to a beam receptor, with calibrations for impedance of the beam. However, CTscans employ digital processing software to interpolate three-dimensional images from multiple, two-dimensional "slices," or scans, taken around a single axis of rotation.

For estimating bone mineral density, CTscans can represent both the actual external shape of a scanned skeletal element and the shapes and sizes of any internal voids, thus effectively addressing the two problems of photon densitometry scans (Fig. 21.2). The attenuation or impedance of the X-ray beam is expressed in "CT numbers" or Hounsfield units (Lam et al. 1998: 561), reflecting the calcium mineral densities within the scanned elements. A clinical product that permits calibration of bone mineral density (BMD), a solution of dipotassium phosphate, is scanned along with the bone specimens as baselines for imaging attenuation (Lam et al. 1998: 562). The bone mineral density, BMD (gm/cm^3) is derived from the three-dimensional imaging.

Lam and colleagues (1998) initially produced bone BMD estimates for elements of goat (*Capra hircus*), using the same scan sites illustrated by Lyman, and compared their BMD results with Lyman's cervid VD estimates. Notwithstanding taxonomic difference among these ruminant species, the values were highly correlated. Because some debate existed over whether density indices are ordinal, they offered both linear regression analysis ($R^2 = 0.47$, $F = 27.80$, $P < 0{\cdot}0001$) and Pearson's rho rank order correlation coefficient ($r_s = 0.68$, $P < 0{\cdot}0001$) between BMD and VD. However, Lam et al. stressed that the correlation masks the fact that CT BMD values for *some* element portions diverged markedly and importantly from those of photon densitometry VD for the same sites. For example, the femoral mid-shaft is the highest-ranked in BMD in CTscans, whereas it ranks seventeenth in VD calculations, results also

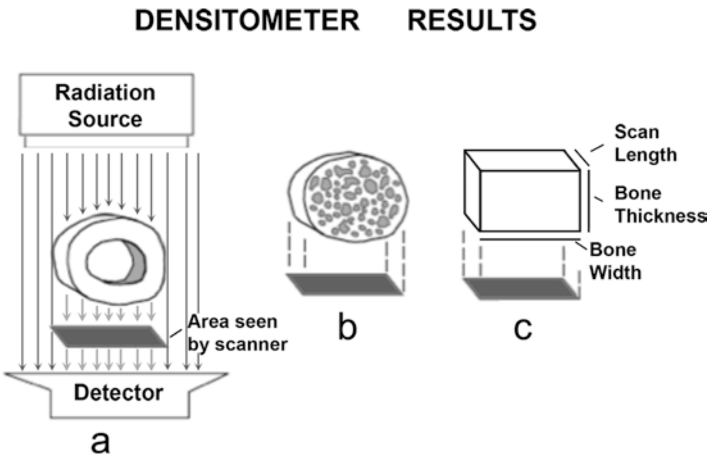

Fig. 21.2 Lam et al.'s (2003) illustration of problems with the photon densitometer correction factor approach, showing the imperviousness of the measure to overall bone shape and the presence, absence, and nature of internal voids. (From Lam et al. (2003: 1703, Fig. 1), used with permission of senior author and Elsevier)

Table 21.2 Lam et al.'s (1998: 567, Table 3) regression and Spearman's rho statistics for the relationships between the log %MAU in the two archaeological assemblages, Kobeh Cave and 'Ain Dara Mound and the bone mineral density values using CTscan-based BMD estimates and photo densitometer based Volume Density (VD) estimates

	Regression statistics			Spearman's statistics	
	R^2	F	P	r_s	P
Kobeh log %MAU by CT	0.56	37.08	<0.0001	0.5	<0.0001
Kobeh log %MAU by VD	0.18	6.30	0.0181	0.40	0·0298
'Ain Dara log %MAU by CT	0.53	31.77	<0.0001	0.69	<0.0001
'Ain Dara log %MAU by VD	0.16	5.25	0.0296	0.40	0.0447

suggested by Elkin's 1995 study. Significantly for studying density-mediated attrition, CTscan BMD values for long-bone *epiphyses* display strong and consistent differences from diaphyses of the same elements that were not displayed in VD values for the same scan sites (Lam et al. 1998: 564). Applying both indices to caprine bones in two Southwest Asian archaeofaunas for which based on other criteria, they expected substantial carnivore attrition, they found that the CTscan BMD values correlated more strongly with log %MAU than did non-shape-corrected photon densitometer VD values (Table 21.2). Lam and co-workers attributed this to the greater realism of CTscans in estimating the actual amount of bone tissue in an element.

Lam et al. (1999) published BMD indices for reindeer/caribou *Rangifer tarandus*, a cervid, wildebeest *Connochaetes taurinus*, an African bovid, common zebra *Equus quagga burchelli*, and wild horse *E. przewalskii*. They used the same scan sites as Lyman's, and sometimes altered sites to adjust to osteological differences between ruminants and equids, and they added some elements such as the petrous temporal. The article details how two calculations were used to estimate BMD, depending upon whether the external cross-sectional outline at scan sites was sufficient for calculating the bone area (BMD_1) or whether internal cross-section of medullary space must be traced to take into account the size and shape of the void within the element (BMD_2).

Lam and colleagues (1999) compared BMD values among all taxa in their samples, plus Lyman's deer and sheep and Elkin's guanaco, the latter three being VD values (Table 21.1). They found that, especially among the ruminant artiodactyls, element BMD values were usually highly significantly correlated ($p = <0.001$). However, true to Kreutzer's (1992) functional anatomical predictions, modest differences are found in such regions as the anterior cervicals, where differences in types of male-male competition probably have favored deposition of more or less bone mineral. The authors recommended that these extant BMD estimates are sufficient for application to most other taxa within the major zoological families represented, thereby sparing other researchers the time and expense of seeking to use CT equipment. Naturally, animals of divergent functional anatomy and osteology should be CTscanned. Lam et al. (2003) later argued that, in the absence of the opportunity to use technology to estimate bone mineral density in various elements, shape-corrected densitometer values can provide a reasonably reliable key to bone durability in bone without internal voids.

In their reviews of bone mineral density estimation methods, Lam and Pearson (2004, 2005) inserted an important methodological note: "Ironically, the increased technological sophistication of density studies have resulted in greater methodological variation than that observed among the original water displacement studies" (Lam and Pearson 2005: 102). They note that one of the main sources of the variability in VD estimates, besides those already outlined here, seems to be variation in different researchers' scanning procedures, which they illustrate by divergent results in simple VD estimates of caprine elements in three studies (Lam and Pearson 2005: 102, Fig. 1). They note that many more researchers have attempted photon densitometer estimates than have done so with CTscanning and stress a need for explicit standardization of scanning procedures, which necessarily differ from the medical uses of single- or double-beam technology to scan bones in living tissues of patients. They thus call for new techniques and methods. As of the time of their publication, the authors were part of the only team to produce CTscan readings for a variety of skeletal elements and species, but they imply that a similar lack of uniformity in technique could emerge in using such technology.

21.1.3 Does a Negative Correlation Exist Between Nutritional Utility and Bone Durability?

Are the skeletal elements most likely to be selected for transport and processing because of their higher nutritional values also the most fragile in the skeleton and therefore, the most liable to be deleted by taphonomic processes? Lyman (1985,

Table 21.3 Lyman's Kendall's tau rank-order correlation coefficients of volume (a.k.a bulk) density with caribou and sheep MGUI

Caribou	**Kendall's tau**
VD:MGUI	−0·080 p = 0·540
Sheep	**Kendall's tau**
VD:MGUI	−0·257 p = 0·047

Data is from Lyman (1985:228, Table 3)

1992) explored whether a negative relationship exists between utility indices and bone VD. If at least some high-utility bones have low volume density values, and some low-utility bones have high density values, he argued, this would present a problem in archaeological inference, because "inverse utility" curves could also result from in-place destruction of less durable elements. His reasoning was that elements or portions with considerable cancellous tissue were both reservoirs of nutrients (Chaps. 5 and 19) and more delicate than elements composed mainly of compact bone.

Lyman (1985, 1992) used Kendall's tau (1985) or Spearman's rho (1992) rank order correlation coefficients to assess the relationship between VD and various of Binford's utility indices, as well as indices developed by others for other animals. His results did not reveal uniform, statistically significant correlations, but they did reveal a consistent trend toward *negative* relations between VD and utility (Table 21.3). He later (1992) elaborated on this analysis by including nutritional data from more animals. This analysis also revealed a trend, though not always a statistically significant one, toward an inverse relationship between nutritional value and volume density (Table 21.4).

Some may consider the existence of a trend rather than consistent, statistically significant correlations reason to dismiss Lyman's claims. However, in view of the problems outlined above in using with VD as an estimator of bone tissue density, it is worth asking whether BMD values derived from CTscans by Lam et al., rather than VD, would produce more compelling results. I explored this with caribou, a species for which MGUI and SFUI as well as BMD are known. Using the $p \leq 0.05$ standard for significance, both results, $p = 0.007$ and $p = 0.001$, would be considered very statistically significant (Table 21.5). These results suggest that further evaluation of the inverse association between BMD and nutritional utility (MGUI/FUI) for various species would be a useful step in zooarchaeological analysis.

21.1.4 What Causes Destruction of More Fragile Elements or Portions of Elements?

Destructive processes affecting skeletal elements include consumption by carnivores, human culinary and consumption practices (marrow extraction, bone grease extraction, mashing and gnawing bone ends), human and animal traffic that crushes less dense bone, and post-depositional chemical and mechanical stresses, including

Table 21.4 Lyman's (1992: Table 2) Spearman's rho rank-order correlation coefficients and *P* values between deer volume density (VD) and various published utility indices for artiodactyl species. These show consistently negative, but not always statistically significant, correlations of utility and MGUI

Utility index: VD	Utility w/ tongue		Utility w/out tongue	
	Rho	*P*	Rho	*P*
Sheep MGUI[a]	−0.295	0.11	−0.349	0.06
Caribou MGUI[a]	−0.116	0.54	−0.188	0.31
Complete-bone FUI[b]	−0.191	0.47	−0.212	0.42
Guanaco meat utility[c]	−0.541	0.004	N/A	N/A
Guanaco modified utility[c]	−0.309	0.09	N/A	N/A
Bison grease utility[d]	N/A	N/A	−0.986	0.002
Bison modified total products[d]	N/A	N/A	−0.308	0.10
Impala[e]	−0.65	0.018	N/A	N/A
Alcelaphine antelope[e]	−0.729	0.009	N/A	N/A

[a] Binford (1981)
[b] Metcalfe and Jones (1988)
[c] Borrero (1990)
[d] Emerson (1990)
[e] O'Connell et al. (1990)

Table 21.5 Spearman's rho rank-order correlation coefficients and *P* values between caribou nutritional utility indices (see Table 20.1) and caribou BMD (Table 21.1)

Utility index: BMD	Rho	*P*
Caribou MGUI	−0.4641	0.00745
Complete-bone FUI	−0.5765	0.00132

the cumulative static loading of sedimentary layers. Whether and how one can tell which actor or other taphonomic process is involved in destruction of skeletal elements is a concern, and the lines of evidence outlined in Section 4 are relevant because actor/effector analysis can more closely specify the main process(es) that impacted an archaeofaunal sample. How to assess the dominant agent(s) of reduction in such assemblages is at present unclear, no "cookbook" approach exists for doing so. However, Chap. 17 provided examples of how various zooarchaeologists have approached this problem. Lyman (2008: 264–298) reviews the issues involved in tabulating such traces, which, like element frequencies, also become aggregate data, and he stressed (Lyman 1994: 335) that it is important to inspect existing specimens for percussion marks, carnivore action, and weathering, all of which are known to be related to processes that contribute to bone attrition, for hints at the processes and actors involved. The next section presents examples of how some zooarchaeologists have used bone mineral density and nutritional indices to explore the overlapping impacts of human selectivity and site formation.

21.1.5 How Can Knowledge of Bone Durability be Employed in Archaeofaunal Analysis?

This question can be rephrased as, is there a way to distinguish *in situ* destruction from selective transport? Lyman (1985) suggested that, in addition to element frequencies, taphonomic and sedimentary evidence must be used to evaluate how heavily attritional processes may have affected an assemblage. For example, high frequencies of carnivore tooth marks or bone reduction patterns typical of carnivores on specimens should alert analysts to the possibility that such actors may have deleted less durable bones from the assemblage. In an application of his recommendations, Lyman (1985: 233) argued that Gatecliff Shelter‘s (Thomas and Mayer 1983) inverse bulk utility pattern in the bighorn sheep assemblage could have been structured by forces other than human selectivity. Carnivore action is evident on specimens, and post-depositional rock falls affected the bone assemblage. He was careful to state that he has not “proved” that attrition rather than selective transport by humans is responsible for the curve. Rather, he urges circumspection in making such behavioral interpretations. Lyman noted that, in contrast, Speth’s (1983) Garnsey archaeofauna shows very little evidence of carnivore action, fluvial transport, or weathering on the well-preserved bones. While skeletal parts of low utility were more abundant than those of high utility at the Garnsey Site, some high utility bones are present in very good states of preservation. Lyman argued that, in this case, the bone durability evidence supports Speth’s interpretation of the assemblage as the product of human decisions based on relative utilities of elements.

Grayson (1988) analyzed the archaeofauna from Last Supper Cave, Nevada, and found a pattern of element representation for *Ovis canadensis* very similar to that of Gatecliff Shelter. Given Lyman’s discussion of differential bone durabilities, he explored these in relation to VD and to MGUI, using Kendall's tau rank order correlation analysis. He proposed that inverse utility curves caused by human selection should show a *significant negative correlation* between MGUI and relative frequencies of elements, expressed as %MAU, which in the the era he was writing, was commonly used – see Chap. 18 (Grayson 1988: 70). By contrast, he contended that, in situations where only dense bones have survived attrition, there should be a *significant positive correlation* between VD and the element frequencies. With the Last Supper Cave assemblage, Grayson found that the relationship between VD:%MAU was positive and very significant, while that between %MAU:MGUI was negative but not significant. Gatecliff Shelter produced a similar result, with VD:%MAU, $P = 0.0001$, and a negative correlation of MGUI:%MAU $p = 0.05$. Without asserting a systematic relationship between MGUI and VD, Grayson inferred that these assemblages were more heavily affected by attrition than by human selectivity. On the basis of bone surface modifications, he concluded that carnivores are the most likely causal agents. Grayson also evaluated Anavik, Binford’s Nunamiut kill-butchery site: the site showed no significant relationship between element frequencies and VD, but did display a highly significant negative correlation between frequency of skeletal element and MGUI, supporting Binford’s description of activities there.

Lyman (1991) built on Grayson's predictive model in evaluating whether and how 67 ethnoarchaeological, archaeological, and paleontological faunas conformed to Grayson's 1988 predictions, using Spearman's rho rank order correlation coefficients. Lyman constructed a nine-cell matrix (1991: 130), with significance values for %MAU:MGUI on one axis and those for %MAU:VD on the other. Lyman's results indicate that the Anavik kill-butchery fauna falls where it "should," as a kill-butchery site from which high-utility elements had been removed, with a significant negative correlation between %MAU and MGUI and no positive correlation of %MAU:VD. Of special note is the fact that, despite archaeological evidence that some archaeofaunas derive from kill-butchery episodes, no *archaeological* sample displayed a similar pattern to Anavik's, although some showed negative correlations of *both* %MAU:MGUI *and* %MAU:VD. Lyman interprets this as reflecting attrition by post-depositional taphonomic processes operating on the original element frequencies produced by human selectivity.

Taking a very different approach to the study of bone attrition, Cleghorn and Marean (2004) argued that the evidence for carnivore, especially spotted hyena (*Crocuta crocuta)*, bone destruction in Pleistocene Eurasian and African archaeofaunas is so pervasive that methodological coping tactics were required. Since actualistic research on hyenas' bone-destroying capabilities in captivity and in the wild (Marean et al. 1992; Blumenschine 1988; Marean and Spencer 1991; Capaldo 1998) are demonstrated, Marean and Cleghorn recommended that zooarchaeologists in any region with such large, bone-consuming carnivores use *only* the highest survival elements and portions of elements to estimate MNE. For long bones, these would be diaphyseal fragments, rather than epiphyseal ends; for skulls, these would be teeth and petrous bones (Bar-Oz and Dayan 2007). See also Marean et al. (2004) for a discussion of ignoring diaphyseal fragments in analyses.

Stiner (2002) objected to this and other arguments for diaphysis-based estimates of abundance on several grounds, citing agreements between shaft-based and epiphysis-based MNE estimates in the Palaeolithic Mediterranean archaeofaunas with which she had worked. Stiner also noted that published captive hyena feeding experiments used sheep elements and body segments, which the hyenas readily consumed. She stated that it was an open question whether the much larger ungulates recovered from Pleistocene archaeological sites would have been so completely reduced by *Crocuta*.

More recently, Janzen and Cleghorn (2010) presented data from experiments in the same hyena colony used by Marean et al., using domestic cattle vertebrae, scapulae, innominates, and femora, some of the latter whole, others broken and with marrow removed. They reported that the extent of bone destruction by hyenas in the experiment appeared to depend upon the social rank of the individual given the elements. Nevertheless, they found that hyenas were capable of demolishing even complete cattle femurs. As with the smaller animals, the hyenas consumed vertebrae leaving only a few scraps. Femoral portions were often consumed nearly completely, but differences were apparent in the treatment of shafts, depending upon whether the hyenas were presented with whole versus marrow-extracted bones. These data suggest that, if hyenas can have access to *raw* skeletal parts discarded by humans, larger axial elements often will be consumed, as will at least the epiphyses of long bones. Thus, the experiments established the species' *capabilities*, as have Lupo's (1995) observations on spotted hyena destruction of uncooked large ungulate elements hunted by Hadza foragers, and Blumenschine's and others' field-based experiments cited above.

However, I believe Stiner is correct to note that not all of *Crocuta's* former ranges displayed the levels of carnivore packing and interspecific competition observed in some parts of East Africa (Chap. 12). Lower rates of bone consumption are hinted at in African areas where hyena populations are less dense (e.g. Lam 1992; Egeland et al. 2008; Kruuk 1972). If at all possible, the prudent zooarchaeologist will seek contemporaneous paleontological information on carnivore species diversity before choosing a counting strategy, and checking both diaphyseal and epiphyseal estimates may be a good way to proceed. This is especially relevant in light of Morin et al.'s (2016) blind tests results, in which estimates based on long bone diaphyses were notably poor estimators of original skeletal element abundances (Chap. 18). Some have contested Stiner's (2002) anatomical region profiling method, but her careful cross checking of epiphyseal versus shaft MNE determinations is an intelligent way to explore the extent of BMD-based attrition, as are Grayson's (1988) statistical explorations.

These matters may seem only of concern to paleoanthropologists, but any zooarchaeologist who believes that their assemblages were affected by some form of serious mechanical attrition and considers using only high-survival elements should consider how this in turn may introduce the potential for sample-size effects, and hence reduced statistical power, in their estimates. Faith and Gordon (2007) used simulation studies to assess whether analysts following Cleghorn and Marean's recommendation to use only high-survival elements risk bringing their sample sizes below levels that produce reliable results. They evaluated sample-size effects on commonly applied measures of association employed to discern the influence of selectivity, such as correlations of %MAU with SFUI (Chap. 20). Their goal was to explore whether decreasing sample sizes affected the rates of Type I errors (in which significant correlations exist in the sample, but they do not in the parent population) or Type II errors (in which no correlation exists in the sample, but a significant one exists in the parent population).

Faith and Gordon used Pearson's rho combined with the Shannon Evenness Index (Chap. 22) to explore sample-size effects may be obscuring patterns of selective transport. They drew from four populations of 1000 "high-survival" artiodactyl elements (Faith and Gordon 2007: 874, Table 1):

1. A parent population structured according to Binford's gourmet utility profile.
2. A parent population structured according to Binford's bulk utility profile.
3. A parent population structured according to Binford's "unbiased" sample, which represented skeletal elements at rates correlated with their nutritional value.
4. An "unconstrained" parent population, structured to include all elements in proportions commensurate with their frequencies in the skeleton, reflecting repeated cases of whole-body transport.

From each sample population, random draws of 250, 150, 100, and 50 elements were made, each 5000 times. The evenness (*E*) of the distribution of skeletal elements and Spearman's rho correlation coefficients of SFUI to element frequencies were calculated for each draw.

For samples from the gourmet and unbiased populations, Type II errors increased as sample size decreased but remained relatively low. However, with bulk transport samples, where all but lowest utility elements are transported, Type II errors jumped from 1.9 to 48.7% as the sample MNE dropped from 250 to 50 (Faith and Gordon 2007: 876, Table 3). They conclude that bulk transport assemblages are especially sensitive to sample size effects. Recalling that the unconstrained parent population had no prior correlation between SFUI and element frequencies, Type I error rates are of interest: these occurred in 10–12% frequencies, regardless of sample size.

Applying the Shannon evenness index to each parent population and sample, the authors note that the bulk and unconstrained use patterns are quite similar, approaching or at 1.000, whereas the unbiased is "intermediate" in evenness (0.842), while the gourmet population, dominated by femora, has the greatest unevenness, at 0.369 (Faith and Gordon 2007: 876, Table 1). Reducing sample size differently affects evenness in samples drawn from the four populations. The gourmet strategy remains distinct from the others, regardless of sample size. At 250, the remaining three samples discriminate well from one another, but at 150 and 100 MNE, the evenness values of the bulk and unconstrained samples begin to overlap, while the unbiased sample remains distinct. At 50 elements, the bulk, constrained, and unbiased samples are indistinguishable. Faith and Gordon illustrate these points with three archaeofaunal analyses for which the data were available: Porc-Épic (Porcupine) Cave, Ethiopia, Die Kelders Cave, and Olduvai FLKN levels 1–2, showing possible sample size effects and possible transport strategies.

To sum up, when sample sizes drop below 150, correlation coefficients may not accurately reflect composition of the parent population. Samples from the relatively even, bulk, and unconstrained populations displayed greater Type II errors than did unbiased and gourmet samples. Bulk sample assemblages have the highest Type II error rates because a lack of correlation of SFUI with element frequencies is quite possible. Faith and Gordon argue that the Shannon evenness index can help analysts distinguish between transport strategies, although bulk and unconstrained transport strategies will produce similar evenness values. One should also recall that, except in mass kill situations, permutations of the bulk or unconstrained transport tactics were probably the *most common accumulators* of archaeofaunal deposits.

21.2 Why Use Only Element Frequencies?

At this point, one may well ask, what kind of an analyst would only use element frequencies to diagnose selective transport or effects of attritional processes? In the fractious debates about equifinality, this simple question often seems to get lost. Bone surface modification data, as citations above show, are key. If any assemblage lacks these data and is important enough to cite from the literature, it is important enough to reanalyze, if the collection has not been lost in the interim (see "Archaeological Sin," Chap. 8).

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Chapter 22
Zooarchaeology and Ecology: Mortality Profiles, Species Abundance, Diversity

Zooarchaeologists by definition have always studied what cultural anthropologists and others now call “multispecies relationships” (e.g. Kirksey and Helmreich 2010). This chapter, Chaps. 23, and 24 review the ecological dimensions of how they study these relations. Zooarchaeologists analyze materials that testify to the interactions of our species, or those of our ancestors, with other species, as our marks and modifications to their remains constitute a kind of “trace fossil” of those relations. Animal remains in archaeological sites, marks of tools on shell or bone, and from later periods, artifacts made from bone, shell and animal fibers reflect those interactions. In case of domesticated or managed animal species, one could characterize these relations as “entanglements” (Hodder 2011), that produce many unanticipated consequences for humans. While Hodder initially concentrated on human – thing relations as loci of entanglement, anyone who has ever worked with domestic animals understands the exigent and often emergent dimensions of such relationships.

Zooarchaeologists have mainly been recipients of methods and theoretical frameworks from ecology. However, over the last 30 years, some zooarchaeologists have contributed to ecology, by providing critical data on the biogeography and regional histories of various species and reporting direct observations of contemporary people that assess whether and in what ways predictions about human decisions and actions drawn from foraging theory are borne out. This chapter reviews the interrelated histories of ecology and English-speaking archaeology, then provides an overview of analytic methods drawn from ecology that have commonly been used by zooarchaeologists.

The concept of ecosystems emerged in the 1930s (e.g. Tansley 1935; Cooper 1957). While the concept has undergone considerable evolutionary change since then (Willis 1997), its diffusion marked the beginning of modern ecological studies. Concurrently with Tansley’s publication, British archaeologists researching hunter-gatherers and early farmers were working with paleobotanists to set ancient people into regional biomes, viewing farmers especially as active agents in landscape modification, and British paleobotanists used archaeological excavations as a source for data to produce regional vegetation histories (Chap. 2, e.g. Clark et al. 1935; for a

D. Gifford-Gonzalez, *An Introduction to Zooarchaeology*,
https://doi.org/10.1007/978-3-319-65682-3_22

review, see Clark 1989). British archaeologists' interest in human-environment interactions were doubtless influenced by the functionalism of contemporaneous British social anthropology, which often incorporated environmental factors (e.g. Forde 1934). Parallel to these developments, in North America, with the writings of Julian Steward (1936), what soon came to call culture ecology emerged. Despite Steward's strong interest in archaeological data as evidence for ecologically related changes in subsistence and social organization (Steward 1949), not until the 1950s and 1960s did many North American archaeologists begin to study humans as parts of ecosystems (e.g. Caldwell 1964; Flannery 1965; Wedel 1953). By the 1960s, "ecology" became a watchword of processual archaeology.

Toward the end of the 1960s, animal ecologists had begun to apply quantitative methods to describing ecological relationships, becoming increasingly rigorous in the formulation of theory over the next two decades. Younger ecologists called for a transition from inductive generalizations based upon the expertise and intuitions of senior researchers to systematic, deductive approaches to testing hypotheses, supported by specific, often statistically based, predictions (e.g. Simberloff and Boecklen 1981). Another concern was whether certain traits of populations – for example, relative size differences among related species with similar ecological niches or shifts in relative frequencies of species with overlapping niches – really resulted from the processes of natural selection such as competition invoked by past generations. Like archaeologists in the 1960s and 1970s (Clarke 1973; Flannery 1967), biologists questioned longstanding assumptions of their discipline and debated what counted as credible scientific evidence for the operation of central evolutionary processes in their discipline. Over the same span, some zoologists began to develop predictive theories of foraging behaviors that drew in part upon evolutionary ecology and in part upon economics (Charnov 1976; Charnov et al. 1976; Krebs et al. 1978; Krebs et al. 1974; Pyke et al. 1977). In the 1980s, applications of patch choice and other optimal foraging models to human foragers began to appear, as will be discussed in a Chap. 24.

22.1 Proxies and Ecological Relations

The processes and relationships that zooarchaeologists seek to study are not available for observation in the present but rather lie in the unobservable past. The relations between archaeofaunal traces and causal processes that produced them in that past are not directly discernable. The previous two chapters have described zooarchaeologists' debates over how to use aggregate element frequencies to identify the specific nature of activities carried out at a site – primary butchery, caching, residential maintenance – or broader behavioral strategies in which animal foods were acquired and handled – hunting, scavenging, specialized pastoralism, etc. Archaeologists are not the only researchers to face questions about whether reliable links actually exist between measurable traits and an unobservable "target". Ecologists studying contemporary animal communities went through a similar span of questioning whether the ecological processes they wanted to study, such as competition, were reliably reflected by traits of the study populations, as asserted by earlier researchers.

Put another way, using aggregate archaeofaunal data rests on the assumption that these aggregate data are reliable *proxies* for specific human behaviors or ecological relations. In science, a *proxy* is a measurement of one physical quantity that is used as *an indicator of the value of another*. (AllWords.com 1998–2017). This chapter, Chaps. 23, 24, and 25 review uses of aggregate data from archaeofaunas as proxies for human decision-making in its social and ecological contexts. Relying on preserved proxies for unobservable processes is unavoidable. To an extent, requirements for linking a proxy and the process or the functional context of its production parallel those for relational analogies (Chap. 3): one can have greater confidence in a proxy if a clear causal or structural link can be stipulated between the proxy and the target processes, actors, or contexts. Preceding chapters have revealed the complications of inferring using element frequencies as proxies for behavioral context.

22.2 Prey Mortality Profiles as Proxies for Livestock Management and Predation

Studies of mortality profiles in archaeofaunas emerged in the 1970s. They built upon research by paleontologists, who in turn had been applying methods and principles drawn from animal ecologists' study of modern population dynamics. Underlying the animal ecologists' work was demographers' research on human populations, which began with late seventeenth centuries and developed in sophistication and predictive accuracy through the eighteenth and nineteenth centuries, as census information was more systematically collected and probability theory evolved (Haberman 1996).

The distance from census data to archaeofaunas may seem great, but methods developed in the first were transferred to the other, in several steps. The purpose of all such work is to assess from static data on age the dynamic processes of age-specific mortality that create the observed frequencies of different-aged individuals in a given population. Such research has roots in business practices of the late seventeenth and early eighteenth centuries, when firms that sold annuities based on compound interest emerged in England. To be financially viable, such businesses needed reasonably accurate estimates of their potential client base's age-specific death rates. The first "life table," showing the survivorship of successive age cohorts, was circulated toward the end of the seventeenth century (Haberman 1996). Over the next two centuries, practical statisticians, or actuaries, refined methods for collecting mortality data and developed probability theory for companies that sold life insurance. Formal census taking by many Western governments in the nineteenth century contributed larger and more reliable data sets, and the separate academic field of demography emerged.

A distinction exists between how the analytic method is applied in research on living populations and its applications to ancient samples. Unlike demographers working with census or other data, archaeologists and paleontologists must ask whether the age structures reconstructed from ancient faunas were caused *only* by mortality processes that affecting ancient living populations, or whether intervening taphonomic effects have influenced patterning of the evidence. It is useful to understand the bases and assumptions of demographic analyses and its applications in paleontological literature before moving on to taphonomic perspectives on mortality profiles.

22.2.1 Cohorts, Life Tables, Death Tables

To analyze population dynamics, demographers traditionally used static information on proportional representation of age classes (*cohorts*) in a living population drawn from census data. Demographic analysis uses derived data called *life table* (lx) and *death table* (dx) statistics. The l_x and d_x figures are *ratio scale statistics*, drawn from raw numbers of persons in different age cohorts, adjusted to a base-100 or base-1000 scale. The classic l_x table is a histogram beginning with 100 individuals at birth, bounded by whatever age intervals the demographer finds useful, e.g. 1 year, 5 years. Each successive age cohort has fewer individuals represented, as proportions of the original, hypothetical cohort die, ending at the age interval when the last individuals die. Most demographic tables based on census data use 1-year intervals, although for some developing countries, where older people may not know their birth years, grosser age class intervals, such as 5–10 year spans, are used for adults.

22.2.2 Applications in Population Biology

In the 1940s, biologists began more closely monitoring regional animal populations by tagging individuals around their times of birth, repeated live trapping, and other means. Edward Deevy Jr. (1947) was among the first to adapt life table and death table formats to animal population census data, as well as culled (mass kill) samples, and other, natural mortality data. He aimed to explore the nature of processes structuring living populations, and distinctive "signatures" of various types of mortality, from d_x profiles.

Deevy drew a distinction between *attritional mortality* and *catastrophic mortality* patterns in d_x profiles. Attritional mortality was viewed as the normal type of deletion of more vulnerable individuals, such as injured, but predominantly, very young and very old members of a population. Such d_x profiles would be the inverse of the living population, representing those animals deleted by everyday processes of natural selection. The second mortality type, the catastrophic, involved the simultaneous deaths of all individuals in local population, as would results from a mass (non-age-selective) cull. This d_x profile essentially presents a "snapshot" of the living population as it existed when the catastrophic death event occurred and could be viewed as much the same as live census (l_x) data.

22.2.3 Population Dynamics in Paleontology

Soon thereafter, paleontologists sought to understand the biology of prehistoric animals by using wildlife ecologists' age structure analysis with fossil samples. Here, proxies for life processes travelled from a discipline where causation could be checked with contemporary observations to a discipline where they could not. To construct d_x statistics, paleontologists used a single species' dental samples, recovered from discrete, localized deposits. The aim of such research was to infer the mode of death from the overall shape of the mortality profile, using Deevy's attritional versus catastrophic distinction. Using such dentally derived d_x statistics, Finnish paleontologist Kurtén (1953) inferred that a catastrophic mortality event had deposited an ungulate sample in a Chinese paleontological locality. Later approaches to population dynamics more closely considered depositional context, assessing whether the animals in the study sample were likely to have been buried where they died, and if not, whether losses due to taphonomic processes could have biased the recovered age sample (e.g. Voorhies 1969).

Paleontological d_x analysis assumes the sample studied derived from a stable population rather than one rapidly growing or shrinking during the time it accumulated. It further assumes that the pattern of age class representation in the death sample is predominantly the result of mortality acting on a living population, rather than being a product of subsequent taphonomic processes. Each assumption is best used with caution and with detailed analysis of the taphonomic history of the source deposits.

22.2.4 Human Paleodemography

Parallel research on historic and prehistoric human skeletal samples, usually from cemetery contexts, developed in biological anthropology in the 1950s and 1960s (e.g. Acsádi and Nemeskéri 1970). As did paleontological researchers, paleodemographers sought to learn more about ancient human populations solely from analysis of d_x data. Recent research has considerably advanced theory and method in the field (Hoppa and Vaupel 2002; Konigsberg and Frankenberg 1994).

22.2.5 Mortality Profiles Based Studies of Herding Practices

In the 1970s, British and Continental European zooarchaeologists began to use d_x profiles, mainly drawn from dental samples, to reconstruct herd management practices of ancient people (Coy 1981; Grant 1983; Payne 1973). The research rests on the assumption that the age structures in archaeofaunal samples reflect systematic, age-specific culling practices as documented in contemporary pastoral management (Cribb 1985; Ingold 1980; Dahl and Hjort 1976). Such age- and sex-specific

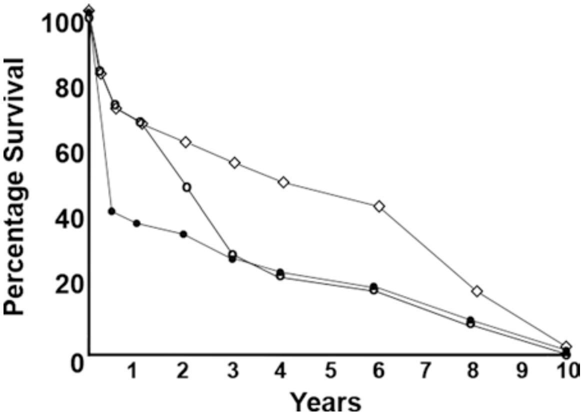

Fig. 22.1 Payne's three hypothetical "kill-off," or herd culling patterns, for meat (open circles), milk (closed circles), and wool (open diamonds) production in sheep or goats (Redrawn from Payne (1973:282–284, Figs. 1–3, redrawn with permission of S. Payne and British Institutes of Archaeology)

slaughtering regimes are aimed at keeping herds at the best balance between their healthy reproduction and their production of a particular consumable. Zooarchaeologists argued that archaeofaunal d_x statistics could reflect these intentions, and, by analogy with contemporary, subsistence-based animal production systems, reveal the type of ancient production system. Payne (1973) contended that, for sheep and goats, the divergent d_x patterns would be produced by kill-off, or culling, according to the desired end products. Meat-focused production systems slaughter most males when they approach full body size, with a few males retained for breeding, accompanied by little offtake of females, source of the herd's resilience. The corresponding d_x profile would thus include a large cohort over the first two years of lifespan, reflecting age-specific male slaughtering, with fewer older individuals, in an attritional pattern (Fig. 22.1). Milk-focused production systems favor survival of females and slaughter most males in each birth cohort before sexual maturity. A corresponding d_x profile would thus include a large cohort of juveniles produced by age-specific male slaughtering and lower numbers of older individuals, in an attritional pattern (Fig. 22.1). Payne set the modal slaughtering age for males as spanning one to three years of age (Payne 1973:Fig. 22.3), perhaps reflecting practices of Anatolian herders. Dahl and Hjort (1976) placed this mode around 18 months for African milk production systems. The divergence reflects strategic choices in widely differing ecological circumstances. Wool-focused production systems favor survival of both sexes through more of their respective life spans, with males usually castrated to enhance their tractability in mixed herds. After infant mortality, a corresponding d_x profile would follow a gradual attritional pattern (Fig. 22.1).

Zooarchaeologists thus used different patterns in age-specific mortality as proxies for differentiated systems of herd and flock management. Payne (1973) and others applying this approach to sheep and goats assigned month values for younger age estimates covered by dental eruption data, while grouping adult animals according to stages of dental wear, as outlined in Chap. 7. Researchers found that actual samples often diverged from idealized patterns, as might be expected in real world situations. Herd managers are concerned with the sustainability of the living herd, which may be managed for more than one goals – for example, both household subsistence and commodity production. Moreover, they change management tactics as they deem prudent, given variable environmental and economic conditions, to realize these goals. Depending upon a herd's prior demographic history and present state, managers adjust age-specific culling and even trade away surplus animals, to enhance herd viability and growth potential (Dahl and Hjort 1976; Homewood and Rogers 1991). Strategic shifts in slaughtering, sale, or exchange may create disparate age-sex patterns among individuals killed on-site from one year to another. Longer-term archaeofaunal accumulations may time-average the outcomes of such strategic fluctuations in slaughtering, and derived mortality patterns may deviate from or blur the idealized culling patterns outlined in Fig. 22.1.

In the four decades since Payne's article, variability has emerged in how researchers actually construct such mortality profiles, as references in Brochier's (2013) critical review show. The basis of age determinations and whether any correction factors were applied must be clearly stated and considered in any comparisons.

22.2.6 Mortality Profiles and Hunting Practices

Reporting on Glenrock Buffalo Jump in Wyoming (Frison and Reher 1970), which dates between the seventeenth or eighteenth centuries AD, Reher (1970) built on the work of Kurtén and Voorhies in constructing age structures of a migrating bison herd driven over a cliff. In a discerning analysis of the data, Reher stated that this bison drive sample was certainly catastrophic, as it sampled an autumn herd over very short time, but that a significant number of young of the year (about 6 months old) and yearlings were absent from the sample. He noted that the overall excellent condition of bone at the site argued against younger animals' skeletal elements being destroyed after deposition. Rather, he proposed that these smaller animals may have been hauled away from the main jumble of adult bodies for butchery in a zone not sampled by the excavation. Reher (1973, 1974) undertook similar studies, constructing life tables from the mortality profiles, at other bison hunting sites.

Levine published a series of papers on ageing equids (Levine 1982) and on mortality profiles for horses that were either hunted or kept as domesticates (Levine 1983, 1990), using ethnographic observations of horse management. Levine (1990) analyzed horse teeth from Dereivka, a site north of the Black Sea dating to the mid-fourth to mid-fifth millennium BP, a time when horses may have been undergoing domestication. She contrasted the generalized attritional and catastrophic mortality models with those produced by killing entire family groups – the most common social units among horses – of animals hunted with a focus on prime-age adults, and of domesticated animals slaughtered in carnivorous husbandry. Levine's textured variation on catastrophic versus attritional mortality profiles parallels that of Payne and is tailored to the species under study, which differs substantially in its behavior, even under domestication, from ruminants.

22.2.7 Mortality Profiles and Hunting Versus Scavenging

In the late 1970s, Klein developed his quadratic crown height ageing method with isolated teeth (Chap. 7), and, with ages derived from it, constructed mortality profiles for Pleistocene and early Holocene African and European archaeofaunas. His approach calculated ages-at-death in months, but then grouped these into 10%-of-lifespan intervals in his mortality profiles (Fig. 22.2). Mortality profiles from different, artifactually defined cultural phases (e.g. Middle Stone Age, Later Stone Age) were compared using the Kolmogorov-Smirnov cumulative frequency statistical test, an appropriate form of analysis for a d_x curve, which is in essentially an inverse cumulative percentage curve.

Klein (1978, 1981) interpreted curves showing statistically significantly different shapes as reflecting hominins' differing approaches to animal acquisition, proposing that attritional mortality profiles were products of scavenging, while catastrophic mortality profiles were the products of hunters' game drives and mass kills (Klein 1982). Thus, Deevy's two descriptive types of mortality profiles, with their names implying causality, were used as proxies for hominin prey acquisition strategies (Fig. 22.2). Klein and his co-workers (Klein et al. 1983; Klein and Cruz-Uribe 1984; Klein et al. 1981) inferred that the hominins associated with southern African Later Stone Age lithic industries – assumed to be anatomically modern humans – more frequently produced catastrophic mortality patterns in larger prey species than did earlier ("archaic") forms of *Homo* then associated with the Middle Stone Age (MSA) lithics in southern Africa. Their inferences were made when the MSA was thought to have been produced by pre-modern hominins, rather than by the earliest anatomically modern humans, to whom it is attributed now (see Marean and Assefa 2005).

22.2.8 Stiner's Revision of Profile Definitions and Age Structure Analysis

Stiner (1990, 1994) took another approach to mortality profile analysis in her study of Middle and Upper Palaeolithic faunas from Italy. She initially reviewed documentation of mortality among wild mammal populations, including predation and non-predation-based, "attritional" deaths. Such actualistic records indicated that non-human predators produce *both* types of the classic mortality profiles, depending upon their predatory strategies. Pursuit predators such as larger canids and pack hunting spotted hyenas, tend to produce attritional mortality profiles, as they run down and pick off slower animals – the injured, very young, and old. Ambush predators, such as most living cats, tend to produce catastrophic profiles because they lay in wait and attempt to capture the nearest animal that passes. Such victims are just as likely to be healthy, prime-age animals as members of more vulnerable age classes. Though classic pursuit predators, wolves hunting in packs, can also set up ambushes. Based on these findings, Stiner suggested renaming Deevy's classic

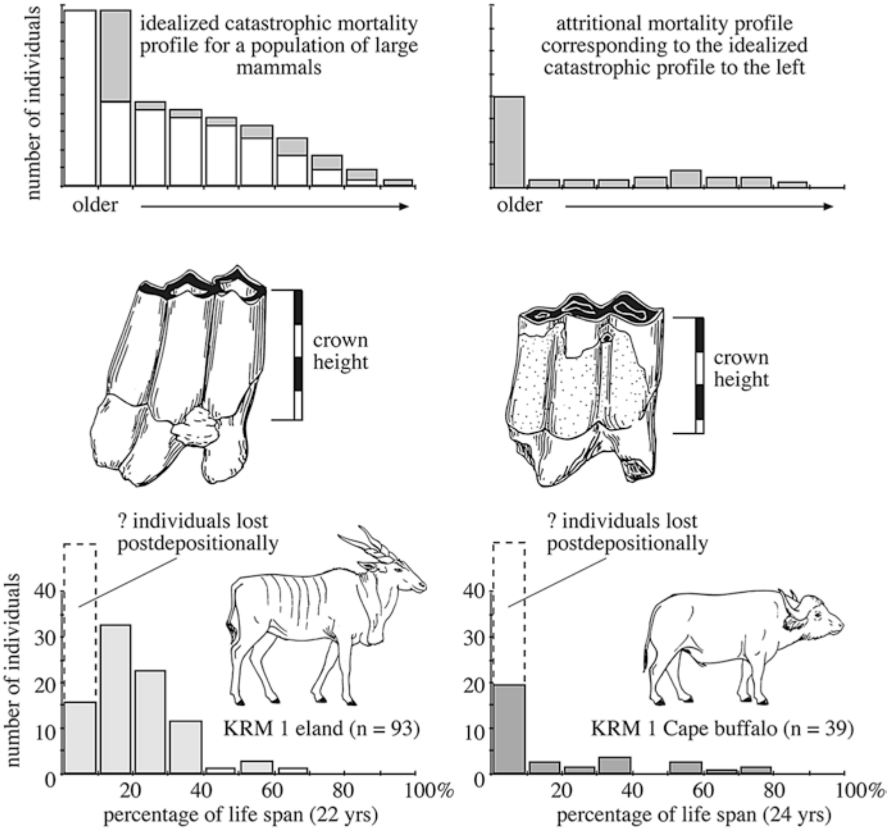

Fig. 22.2 An example of Klein's (1983: 40, Fig. 2) use of Deevy's mortality profile analysis, using crown height-based ages from South African archaeofaunas. (Used with permission of the author and *Annual Reviews*)

mortality profiles to eliminate their perhaps misplaced implications of causality. She suggested the "U-shaped," replace "attritional" mortality profiles, and "J-shaped," or "living structure," replace the "catastrophic" mortality profiles. Based on her analyses of archaeological and ethnographic records unambiguously associated with anatomically modern humans, Stiner noted that modern humans tend to produce a third mortality profile, the prime-age dominated profile.

In her study comparing Middle Palaeolithic (Neanderthal associated) and Upper Palaeolithic (*Homo sapiens* associated) faunas, Stiner (1994) considered that sometimes-imprecise age-at-death estimation methods could, for her purposes, be replaced by tripartite age-at-death categories, applicable to either dental or postcranial evidence:

1. Juvenile (first 20% of maximum lifespan);
2. Prime (middle 50% of maximum lifespan);
3. Old (last 30% of maximum lifespan)

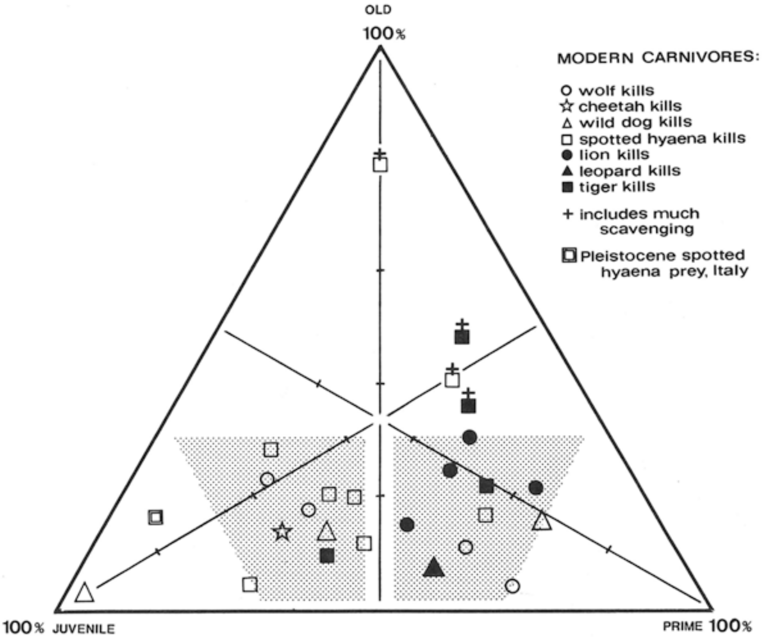

Fig. 22.3 Stiner's application of the ternary plot, displaying three general age classes, juvenile, prime (adult), and old, in this case showing aggregate predation patterns of nonhuman predators (Stiner 1994:299, Fig. 11.5, used with permission of the author and Princeton University Press)

She argued that these three subdivisions are efficacious because they are sufficiently broad to eliminate errors inherent to any one of several ageing methods (Chap. 7), are accurate, and may be realistic because they represent "target" prey classes for the predators involved. She displayed frequencies of these three age groups in the form of ternary plots, which have a long history in optical mineralogy and other geological subfields (Fig. 22.3).

Stiner (1994) placed mortality patterns created by modern ambush, pursuit predators, scavenging carnivores, and modern human hunters into this system. Ternary plots showed differences among such actors, which at the time she did not subject to statistical assessement. Stiner then compared age structures in ungulate dentitions from Upper Pleistocene deposits in central Italy: those likely on the basis of other lines of evidence to have been created by several diffferent actors: spotted hyenas, Neanderthals making Middle Palaeolithic stone implements, and anatomically modern humans who created Upper Palaeolithic samples. Clear differences were discerned between mortality profiles produced by modern humans and hyenas. However, some Neanderthal samples more closely approximated hyena den materials (U-shaped) in age structure, while others more closely resembled those of the modern humans (prime-dominant). Stiner interpreted this as reflecting Neanderthals' more variable approach to acquiring larger mammals than documented for modern humans. One initial problem with the ternary plot approach was that it was difficult to use statistical tests to assess the degree of difference between datasets displayed in this manner. Weaver et al. (2011) published a method that permits such comparisons.

Stiner's approach, like Klein's, used mortality profiles as proxies for hominin and nonhuman foraging strategies. In this case, her argument for the use of such proxies was supported by actualistic data on mortality patterns generated by a range of carnivores as well as by anatomically modern humans. Stiner's use of epiphyseal ageing methods and inference of prime-dominated profiles from archaeofaunas have been criticized on taphonomic grounds (Chap. 21), but her choice of a broad age and multiple lines of osteological and contextual evidence (Stiner 1994) bears careful study as a model for using actualistic data to read archaeofaunal assemblages.

22.2.9 Is the Sample from a Stable Population?

An assumption underlying all zooarchaeological mortality profile analysis is one shared with paleodemography: the mortality profile represents a population in a stable state over time span the sample accumulated. This means that neither fertility nor mortality was undergoing major changes during that period. In wild populations, a lack of stability would involve changes in recruitment (gross fertility, immigration) or mortality rates. Despite documented cycles of "boom and bust" in some species, wildebeest, arctic hares, and arctic foxes, for example, it is assumed that these would be time-averaged in archaeofaunas. The assumption of demographic stability may be more problematic in the case of domestic species, for which the main cause of mortality is age-specific human culling, as has already been noted. Short-term accumulations, for example, that of a camp occupied for a few months by mobile pastoralists recovering from a drought-induced crash in livestock numbers, may present an idiosyncratic mortality profile, rather than the modal pattern. Here, contextual data may provide clues to duration and repetition of occupation that can help understand the diversity of mortality profiles from a single economic group.

22.2.10 Complicating Factors in Mortality Profile Analysis: Transport and Taphonomy

The possible effects of age-specific transport and differential bone preservation complicate mortality profile analysis. Selective discard versus transport of large prey carcass segments may systematically affect what the analyst has to work with, introducing age-specific bias. Binford (1984) contended that Klein's mortality profiles analyses of southern African archaeofaunas did not sufficiently consider effects of selective transport. Binford argued that, in very large species, heads of younger individuals might be transported to a residential base, whereas bulkier heads of older individuals would be discarded in the field, biasing the mortality profile of the species. Transport considerations could similarly bias accumulation of dentitions of large versus small species at a home base. Binford also asserted that independent lines of evidence must be used to support the most fundamental assumption that the dentitions entered site deposits through human predation and accumulation. In an extended review of *Vertebrate taphonomy* (Lyman 1994), Marean (1995:68) noted that deciduous dentitions and immature alveolar bone are more fragile and liable to postmortem destruction than are adult teeth and bones. This fact has been considered by paleodemographers working with human skeletal populations for some time (Acsádi and Nemeskéri 1970; Buikstra 1981). Klein and Cruz-Uribe (1984) discussed destructive effects of post-depositional compaction and diagenesis on bone, and Klein (1989) further explored this topic in light of Lyman's (1984, 1985) and Grayson's (1989) research on bone tissue density and survival.

Analysts working with domestic fauna might be tempted to assume that age-related biases due to selective transport would not apply to their samples. However, slaughtering and subsequent handling of different-aged – and sized – members of a domestic species could create similar biases. Therefore, a case should be built explicitly for why such effects *did not* operate in the formation of a studied sample.

Munson (2000) argued that consumption by dogs and other scavenging, can differentially destroy more immature animals' delicately constructed mandibles and crania and the teeth they contain – some of which are still mineralizing. Munson and Garniewicz (2003) experimentally investigated the age-specific taphonomic effects of dogs. Over the experimental period, they offered six to eight half-mandibles of white-tailed deer (*Odocoileus virginianus*) and domestic sheep of various ages at a time, totaling 198 specimens, to two medium-sized dogs. Roughly half the mandibles were in a raw state, and half had been cooked. Table 22.1 summarizes their results, showing a radical difference in mandible survivorship in individuals ≤30 months versus those ≥30 months of age. Survival rates of immature animals' that came loose and isolated from the mandibles during carnivore consumption were better (Table 22.1) but nonetheless much lower than those of older animals. The experimental data thus support Munson's original assertion that are likely to have lost a differentially greater proportion of the remains of very young animals. Although Munson and Garniewicz focused on carnivore damage, the age-based differences in bone strength and density they document would also affect mandibular survival in the face of other taphonomic processes. González et al. (2012) undertook parallel studies of density-dependent loss of bones due to either or hydraulic transport, showing that lighter, immature elements weather more quickly and are more readily transported by flowing water.

As with site formation issues, discerning differential preservation of older versus younger age classes has no simple solution. However, analysts can engage in several analytic operations to assess whether a sample is appropriate for mortality profile analysis.

1. Explore selective transport or attrition with rank-order correlations of element frequencies with MGUI/FUI, on the one hand and an index of bone tissue density, on the other (VD or BMD), as recommended by Grayson and Lyman and outlined in Chap. 21.
2. Inspect dentitions or age-diagnostic postcranial epiphyseal zones for surface modifications that reflect butchery, culinary processing, carnivore action, and other taphonomic effects that could selectively bias a sample.
3. Check age determinations from a dental sample against those from epiphyseal fusions.

Marean (1995:68) found that unfused epiphyses in postcranial antelope elements from GvJm46, a terminal Pleistocene site near Nairobi, Kenya, in effect "filled in" a substantial proportion of the youngest age cohort of individuals missing from the dental sample. Zeder (1991) determined age classes from both dental and postcranial remains, and Stiner (2002), advocated for a similar comparative approach to element survivorship. Given our indirect and imprecise means of monitoring site formation processes, analysts can probably never be completely certain of the effects of selective transport or selective destruction on an assemblage. However, simply because details of the extent of such influences are imprecise, their possible effects cannot be ignored.

To sum up, mortality profiles have sometimes proved a good proxy for ecological relationships and processes zooarchaeologists hoped they would, but other times, they have not. With circumspection about taphonomic processes, mortality profiles are useful for exploring domestic herd management tactics at a local scale, and, with multiple localities sampled, regional patterns of livestock use. Using mortality profiles as stand-alone proxies for hunting, scavenging, or other, higher-order behavioral complexes has proved to be fraught with theoretical and methodological difficulties. Paralleling the equifinality problems encountered with element frequencies as a proxy for adaptive strategies and behaviors, mortality profiles are now seen as products of several possible causes and therefore poor proxies in and of themselves. They are best used after rigorous review of taphonomic evidence and in conjunction with other, independent lines of evidence concerning site formation and human behavior.

22.3 Measures of Community Structure: Taxonomic Richness, Diversity, Evenness

Turning from mortality patterns to characterization of assemblage composition as a whole, several approaches drawn from ecologists' toolkit have been used by zooarchaeologists. Biologists who explored the systematic relationships of plants and animals in ecosystems developed simple quantitative measures to describe the numbers of species and the relations among them. Zooarchaeologists using archaeofaunas to explore humans' ecological relationships face similar needs to quantify the numbers and diversity of taxa in their samples. Given that their research emerged decades after that in ecology, they borrowed a number of its tools. This section reviews some of the most common measures of taxonomic richness, diversity, and evenness. It notes how these measures have been used not only as descriptive tools but also as proxies for unobservable processes. This chapter's introduction indicated that problems with proxies are not solely confined to zooarchaeology, as ecologists questioned whether some measures actually reflected the processes with which they were initially assumed to be linked. This section outlines some of the zooarchaeological issues these measures have been used to address, and what problems have been encountered in their application.

22.3.1 Taxonomic Richness

One measure is *species (or taxonomic) richness*, which is simply the number of species or other taxonomic units in a sample population, variously defined as a biological community or a geographic region. Some researchers may use taxonomic groupings above the species level, such as families or orders (Lyman 2008:174–185). In ecology, data are collected by sampling in transects or another areal unit. Census methods could include aerial survey of larger, herd living animals, live trapping small animals, and other means deemed sufficient to sample enough individuals to obtain a representative sample. Species richness as a count should be straightforward, although a substantial literature exists on problems that different sampling strategies present for comparing species richness and diversity (see Gotelli and Colwell 2001).

22.3.2 Species Abundance

Taxonomic richness does not take into account the fact that some species are very common and others are more rare in ecosystems. In the arctic, lemmings are much more abundant than are arctic foxes. *Species abundance* describes this fact. In ecology, species abundance was classically displayed as a histogram, with the x-axis being the *number of individuals* counted in each species, from 1 to n, and the y-axis showing the *number of species* enumerated, running from 1 to n. Either x or y may be expressed on a logarithmic (log) scale, if the counts of taxa or individuals are otherwise too great to conveniently display as a histogram. In the mid-twentieth century, ecologists debated causes of the apparently universal tendency for many species to be represented by only a few individuals in samples – the "hollow curve" in such histograms. Longer-term, iterative sampling of target areas and populations produced less skewed estimates of species, revealing that the area and time spans over which species are sampled can affect estimates of taxonomic richness and abundance (Magurran 1988). Because a sample's taxonomic richness and abundance data are used to calculate species diversity and evenness indices of a given sample, this is a critical consideration. This variant of sample size effects will be discussed in Sect. 22.4.

The sections that follow will exemplify the applications of various measures based on taxonomic abundance using a hypothetical set of sample "types" – colored Ping-Pong balls. The "parent population" consists of a bin containing 500 Ping-Pong balls: 300 are white, 150 are yellow, 40 are blue, and 10 are red.

22.3.3 Taxonomic Diversity Indices

This usually involves using species as the "types" in the calculation, and number of individuals in the species in the counts. However, other types could be used equally well, including higher-level Linnaean taxonomic categories (genera, families, orders), or taxa with certain habitat or feeding preferences, such as moisture-adapted vs. arid-adapted rodents, or carnivorous versus herbivorous fishes.

Several methods for calculating diversity indices exist. One widely used set of approaches, the Shannon-Wiener index, was developed by the information theorist Shannon (1948). This calculates the likelihood that one can predict the species (or other type) affiliation of the *next individual* drawn from a population, using the taxonomic richness and taxonomic abundance statistics already generated for that population. Using the example of the four different colors of Ping-Pong balls, this would show your chances of pulling a ball of a given color on the next draw. In a population with low diversity, one's probability of correctly predicting this would be higher, whereas in a highly diverse population, one's probability could be lower. The Shannon-Wiener index of diversity, H′, is calculated as:

$$\mathrm{H}' = -\sum (p_i)(\log_c p_i)$$

also written as:

$$H' = \frac{N \ln N - \sum (n_i \log_e n_i)}{N}$$

where N = the total number of individuals of all species

n_i = the number of individuals of species i

$\log_e$ = the natural logarithm, also written ln

p_i = the proportion of individuals of species i.

The minimum value of H′ is 0, when a community has only one species, and it increases as species richness increases and species abundances vary. In the case of the Ping-Pong balls, with 4 color "types" in the sample in the proportions noted above, H′ = 0.95, as calculated by an online tool for calculating this and other diversity indices (Young 2014).

22.3.4 Taxonomic Evenness

Biologists may wish to know how *equitable,* or *even,* a sample's taxonomic abundances are in relation to one another. This is described by the *species evenness* statistic, which uses the Shannon-Wiener diversity index, H′, to express how similar the per-head numbers of different species are within a given population or ecosystem. Pielou's (1966) measure of species evenness, widely used for many years, divided H′ by the natural logarithm of the species richness in the sample, called ln(S):

$$J = \frac{H'}{\ln(S)}$$

where H′ = Shannon Weiner diversity index.

S = total number of species in a sample

This yields a number between 0 and 1, with 0 reflecting no evenness and 1 reflecting complete evenness. In the case of the Ping-Pong balls, there are four "types," with H′ = 0.95, and the natural logarithm of 4 = 1.39. Thus, J = 0.95/1.39 = 0.68, a number reflecting evenness around midway between the two extreme values. Other evenness measures have been proposed in ecology (e.g. Heip 1974; Magurran 2004).

When and how would zooarchaeologists apply such methods? No sane practitioner would assume that archaeofaunal collections are truly random samples of fauna around a particular archaeological site, from which once can reconstruct taxonomic abundances of the past. However, the Shannon-Wiener index, and various evenness measures have commonly been used to characterize and compare artifact types or faunal taxonomic diversity among samples (e.g. references in Grayson and Delpech 1998, 2006). Applying the indices, archaeologists make no assumption that the assemblage reflects a randomly sampled subset of a broader, ancient ecosystem. Instead, they use Shannon's index, originally developed to deal with bits of information rather than biological entities, simply to *assess and compare assemblage diversity*.

When zooarchaeologists analyze archaeofaunal samples, they must consider that their samples have passed through two filters that do not normally affect ecological data, as well as the same sample size problems that affect ecologists' species richness and abundance estimates. The first set of filters are taphonomic effects, as explored by Schmitt and Lupo (1995) with a set of Fremont archaeological faunas, specifically focusing on the role of nonhuman accumulators that used the same shelters as humans, potentially skewing NISP-based species abundance estimates. This study reflects the value of systematic analysis of archaeofaunal specimens, using criteria of bone surface modification derived from actualistic research, in conjunction with measures of sample similarities or differences (Schmitt and Juell 1994). The second set of filters is recovery methods' (screen mesh size, etc.) effects on smaller taxa, originally discussed in Chap. 8. Implications of recovery-related effects on terrestrial prey of smaller body sizes, and hence on diversity estimates, have been discussed by Stahl (1992), as they have in relation to diversity estimates in fishes (Reitz and Wing 2008; Zohar and Belmaker 2005).

For zooarchaeologists, low species diversity and/or a very uneven representation of taxa may reflect relatively narrow diet breadth, or prey specialization, while more generalized strategies will be reflected by taxonomically diverse faunas, which could nonetheless be even or uneven.

22.4 Coping with Sample Size Effects: Species Area Curves in Ecology and Archaeology

A pervasive problem in species abundance estimates is that, if some species are very rare, they may not be captured in smaller-scale sampling. This is as true of archaeofaunal samples as it is with ecological census data. A simple thought-experiment can illustrate the problem. Imagine again that bin holding 300 white, 150 yellow, 40 blue, and 10 red Ping-Pong balls. If you were instructed to close your eyes and draw 25 balls without replacing them, you would be highly likely to get white and yellow ones, you might get a blue one, but your chances of retrieving a red one are rather low. Your estimate of Ping-Pong species richness from this draw might be 3, or even 2, and your species abundance data might show real skewing away from that of the parent population. However, if you were to draw out 100 balls, your likelihood of finding blue and red balls increases, and your estimates might more closely approximate the composition of the parent population. Drawing 250, half the parent population, greatly improves odds of doing so, and so forth.

Ecologists, paleoecologists, and archaeologists must deal with *sample area* effects, that is, the likelihood that more rare species are less likely to be represented in smaller-scale samples than they are in larger-scale ones. As the simplistic Ping-Pong ball example shows, this can introduce uncertainty about estimates of species richness and species abundance and all the statistics that incorporate them. Unlike ecologists, archaeologists often cannot control the different sizes of archaeological samples they wish to compare, nor can they often return to the “sample tract” to expand the sample, as might be possible for ecologists who encounter such difficulties.

Quite early in the field’s history Grayson (1981) warned that sample size can introduce complications into archaeological uses of species richness and diversity indices. Grayson examined the frequencies of deer in seven successive occupational phases at Snaketown, Arizona, a Hohokam village, and found that this relatively common species is less abundant in larger samples (as more rare species made their appearance in species richness and abundance), and that a statistically significant inverse relationship exists between deer abundance and sample size. He puts the matter well in the summary of his analysis:

> As a result, it is no longer clear whether these relative abundances are measuring changing abundances of deer through time, or are instead being determined by differing sample sizes across phases. That is, the significant negative correlation between sample size and the

> relative abundance of deer across phases suggests that these relative abundances may not be a valid measure of the relative importance of deer characteristic of Snaketown phases (Grayson: 1981:78).

In this case, Grayson used Spearman's rank-order correlation coefficient to explore this issue, concluding that sample size is significantly correlated ($p < 0.05$) with decreases in the abundance of deer, as counted by MNI.

Grayson (1984) and others (see Lyman and Ames 2007 for detailed citations) raised a caution concerning a critical difference between what is counted in ecological species richness estimates and that counted in zooarchaeology, paleontology, and paleoethnobotany. Ecologists produce species richness by counting organisms – beetles, mice, Douglas fir trees – whereas zooarchaeologists, paleontologists, and paleoethnobotanists usually reckon NISP by counting the *parts* of organisms – bones, bivalve shells, plant parts. Chapter 18 noted that one of the conditions of parametric tests that may not be met by archaeofaunal samples is specimen independence, particularly when dealing with stratified sites. The measures of association between sample size and species richness that were developed in ecology, such as regression analysis and rarefaction (see below) assume specimen independence. Thus, using such measures in zooarchaeology requires first exploring and then documenting why specimen independence can be assumed – when one is comparing single component samples from eight widely dispersed sites where specimen interdependence is highly unlikely, for example. Those dealing with stratified sites face more challenges for reasons outlined in Chap. 18, and may wish to use specific, non-repeating measures, such as NDE, which may substantially affect the size of their taxonomic richness totals.

22.4.1 Regression Method Explorations of Sample Size Effects

Lyman and Ames (2007) note that regression analysis has been the most used approach to exploring sample area effects. This approach makes bivariate plots of a measure of overall sample size as x, which in zooarchaeology is NISP, against the number of taxa as y (species/taxonomic richness), then fits a regression curve to the points (Chap. 18). Grayson (1984:131–167) presents a textured and clear exploration of the relation between sample size and species richness, using regression analysis. He argues that those seeking to explain of strong differences among species richness in different samples should begin with considering whether divergences in NISP may underlie these. In his exploration, Grayson plotted species richness against NISP on a semi-log or log-log scales, which he argued, produce transformed data amenable to linear regression analysis. Grayson suggested several tactics for dealing with cases that display a statistically significant relation between number of species and sample size. One is to examine outliers, data points with the greatest positive or negative residuals in relation to the regression line, to determine if something other than sample size effects could be determining these (e.g. Grayson

1984:148–151). Grayson's exploration of the Prolonged Drift dataset (Gifford et al. 1980, see datapoint with arrow in Figure 18.8) in an earlier section of his 1984 book on relations of MNI to sample size may clarify what outliers can tell us. Grayson found that the value for warthog (*Phacochoerus aethiopicus*), fell far off the regression line of log MNI/NISP to log NISP (Grayson 1984:75–76). He notes that data provided in the report indicate this species diverges from other wild and domestic ungulates in body segment representation, perhaps reflecting butchery practices.

Grayson (1998) used a variant of the outlier approach when analyzing small mammal species richness in trans-Holocene samples from Homestead Cave, Utah. He was interested in exploring whether the Homestead small mammal sample might reflect shifts in Great Basin moisture history as predicted from ecological research on the relation of moisture to species richness in arid environments. He first plotted log NISP against log Taxa >1 NISP), to discern species area effects, finding that in 10 of 13 samples NISP predicted richness highly significantly ($r = 0.92$, $p < 0.0001$) but that three samples did not r = 0.88, $p > 0.10$), the latter falling along a regression line with another slope. These happen to be the three earliest samples from the cave, dating to the moistest period of the Terminal Pleistocene and Early Holocene. Thus, Grayson considered himself justified in interpreting general trends in small mammal species richness in the Great Basin.

Butler (1994) used several of Grayson's tactics for exploring screen and sample size effects in a geographically broad sample of fish archaeofaunas associated with the Lapita archaeological tradition, which represents the first human colonists of Melanesia and western Polynesia. Butler's ultimate goal was to explore whether Lapita people used similar or divergent fishing tactics over their entire range, but her systematic approach to exploring recovery effects and sample size variations in archaeofaunal data repays close reading, decades later, by zooarchaeologists pursuing other research questions.

As Lyman and Ames (2007) stress, a statistically significant relation between sample size and species richness it does not necessarily mean that sample size is *causing* the variation (Chap. 18), but rather than one should explore the data further to determine alternate causes before using the samples' species richness comparisons to narrate shifting ecological conditions or human behaviors.

22.4.2 Rarefaction

To cope with the problem of sample area effects on species richness, some zooarchaeologists have imported the method of *rarefaction* from ecology to assess whether species area effects may hold among samples of differing sizes. Baxter (1994) proposed that, because archaeological specimens are neither randomly nor normally distributed throughout archaeological samples, the best way to explore causes of differences in assemblages of disparate sizes are rarefaction techniques (see comments above on specimen independence).

Ecologists Gotelli and Colwell (2001) explained that rarefaction analysis is based on the fact that species richness tends to increase with greater sample size, both in numbers of individuals enumerated and of numbers of types sampled. As sample size increases, so does an “accumulation curve” of species richness, which can vary in its steepness according to sample richness and evenness. This explores the problem of comparing smaller with larger samples by evaluating whether these could have been drawn from the same sampling universe. Rarefaction enables this by working *backwards* from a total sample, analyzing means of estimates of richness while stepping down the size of the samples, as bounded by curves defining the 95% confidence intervals of the mean estimates. As Gotelli and Colwell (2001: 381) state,

> Accumulation curves, in effect, move from left to right, as they are further extended by additional sampling. In contrast, rarefaction curves move from right to left, as the full dataset is increasingly “rarefied.”

Rarefaction thus iteratively constructs taxonomic lists from incremental samples drawn from a whole assemblage, which is best accomplished with one of several open access computer applications (Holland 2003; Hammer et al. 2001). For discussions of rarefaction in zooarchaeology, see Reitz and Wing (2008:110–115), Lyman (2008), and Lyman and Ames (2007). Rarefaction, Lyman and Ames (2007:1987) argue, permits researchers to assess whether their samples’ species richness can be compared with richness of another sample of different size, “without fear of differences in sample size obscuring results or producing false results (if we ignore problems of specimen interdependence).”

I used rarefaction to assess whether sample size effects, rather than documented regional climate change, were responsible for changes in taxonomic richness in a 6000-year Holocene sample of archaeofauna from Ele Bor A, a stratified rockshelter in far northern Kenya (Gifford-Gonzalez 2003). With the advice and help of colleagues Eli Geffen (Tel Aviv University) and Irit Zohar (University of Haifa), I applied rarefaction analysis to explored species richness Ele Bor A samples, calculated using the Brillouin Diversity Index, rather than the Shannon–Wiener Diversity Index. The Brillouin Index (H) is nearly identical to the Shannon-Wiener function but takes into account that the samples are not random and the total number of species is unknown; it is sensitive to abundances of rare species in the sample (Krebs 1999). It is calculated as:

$$H = \frac{1}{N}\log_2\left(\frac{N!}{n_1!n_2!n_3!\ldots}\right)$$

where N = the total number of individuals in entire collection.

$n1$ = the number of individuals (NISP) belonging to species 1

$n2$ = the number of individuals(NISP) belonging to species 2, etc.

Rarefaction results (Fig. 22.4) at EBA. Horizon D, the oldest sample, had the lowest taxonomic richness, while species richness increased markedly through Horizons C and B, diminishing with the topmost Horizon A. Species richness for

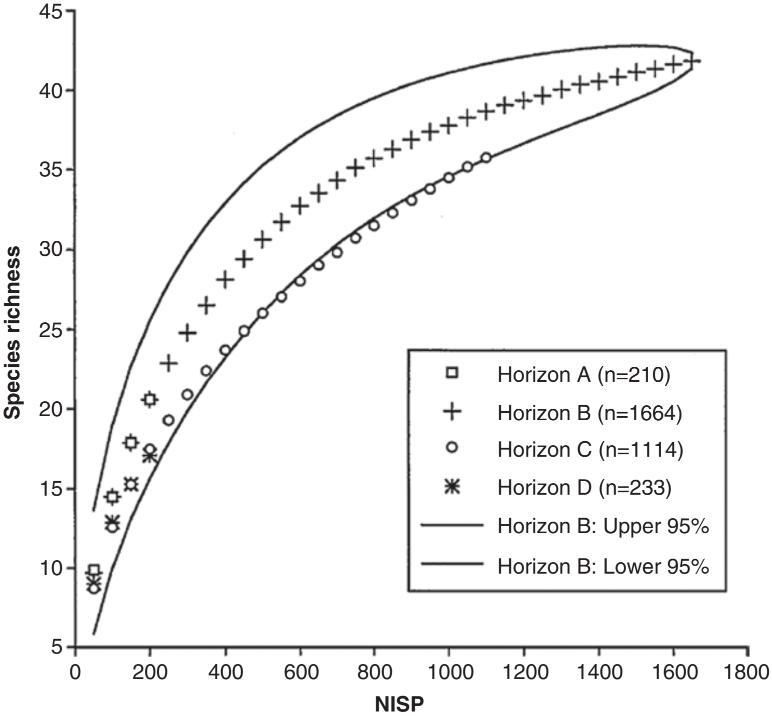

Fig. 22.4 Example of application of rarefaction to archaeological assemblages from Ele Bor, applied to shed light on whether the change in species richness between Horizon C and Horizon B is likely to be an artifact of sample size differences, rather than a probable shift in species taken. This comparison did not take into account the possibilities of specimen interdependence (From Gifford-Gonzalez (2003:100, Fig. 5, used with permission of Springer)

Horizon B (42 taxa) and Horizon C (36 taxa), fall within the 95% confidence limits of the species richness rarefaction – Horizon C only just. I felt justified in interpreting this as suggesting that sample size was unlikely to be responsible for the drop in numbers of larger gazelle species relative to those very small bovids. Rather, I interpreted this as the probable result of increasing regional aridity over the time that Horizon B accumulated. However, when my ecologist colleague suggested rarefaction – as well he, as an ecologist, might – I had forgotten the specter of specimen interdependence raised in Grayson's early work and now consider my interpretations of these data with a bit more caution.

22.4.3 Sampling to Redundancy (STR)

Another method for assessing whether sample size may be affecting species richness is called sampling to redundancy (STR). This involves plotting the species richness (in zooarchaeology, most commonly, as NISP) of successive samples

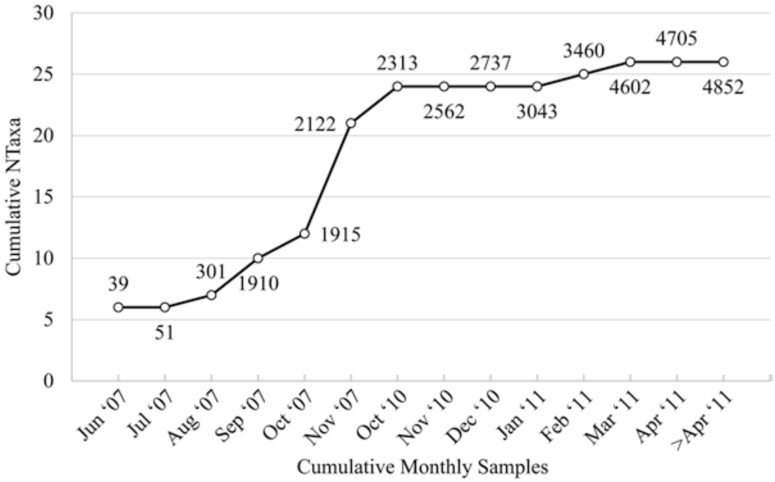

Fig. 22.5 An example of sampling to redundancy with the Bonny Doon Site (CA-SCR-9) archaeofauna. Two rounds of analysis by Potenzone and Nims produced species richness estimates at specific times. Note that the curve is steeper at first and then levels off as sample size approaches NISP = 3000, but species were still added until sample size reached 4600 (From Nims et al. (2016:26, Fig. 4), used with permission of R. Nims and Malki Museum)

drawn from the same sampling tract (or site). This is a form of cumulative frequency curve, the number of taxa being revised with each new increment. Lyman and Ames (2007:1987) argued that STR curves are a variant of species area curve and that, "The STR protocol is a dynamic analytical procedure – add or accumulate individuals or samples – that has as its purposes allowing one to determine if, and to empirically demonstrate that, the total collection is representative of the variable of interest." Figure 22.5 shows use of sampling to redundancy with the fauna from CA-SCR-9, a site in the uplands of northern Santa Cruz County, California (Nims et al. 2016). As has been described by Lyman and Ames (2007), STR curves are initially steep, as each new increment adds a substantial number of taxa, then at some point, taxonomic richness levels off, as demonstrated in the SCR-9 curve. We used STR to decide whether species richness in the sample, as accumulated to 2011, was representative enough of the site as a whole to forestall further analysis before final reporting in a publication. However, we also know that the richness data produced by the analysis could be used as Lyman and Ames suggest, in further, inter-assemblage comparisons.

To sum up this chapter, aggregate archaeofaunal data take many forms, from skeletal element frequencies, bone surface modifications, taxonomic abundances, and age structures. To compare their data to those of other analysts, zooarchaeologists have imported a number of measures from ecology. While ecologists do have to consider that their samples are never perfectly instantaneous (Lyman and Ames 2007), zooarchaeologists and paleontologists face different challenges. First, the amount of time over which a sample accumulated may be highly variable and not amenable close specification. Second, a long time span, and many transformative processes – only sometimes specifiable – has elapsed between the events creating an archaeofauna and its recovery. The disparate and only partially specifiable histories of different archaeofaunal samples requires that comparisons among them be based in thorough understanding of what *can* be known of these histories. Assessing taphonomic impacts on age structures, species counts, or element frequencies is one such line of prudent investigation. Effects of recovery methods are another area for assessment – for example, should one expect divergent species richness simply because samples were recovered with different screen sizes? Finally, when comparing archaeofaunas of differing sample sizes, how much of the difference in one's basic data and derived statistics stem from species area effects?

Regardless of the measures employed, the fundamental question remains the same: how certain can we be that the measure used can stand as a proxy the "target" processes or actors we wish to study – and on what grounds? This chapter has reviewed some examples of zooarchaeological proxies and what has been learned about some of the strengths or weakness of linkages proposed between them and various the research targets for which they were intended to stand. Here, once again, the best advice on how to deal with such issues is Lyman's recommendation that closed Chap. 18: be explicit about one's assumptions and procedures. This permits others to assess whether and why your analysis is plausible. Chapter 23 explores more recently developed, and, in two cases, more clearly specifiable, relationships between proxy and target.

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Chapter 23
New Ecological Directions: Isotopes, Genetics, Historical Ecology, Conservation

This chapter provides an overview of three areas of research collaboration for zooarchaeologists. The first is stable isotope analysis, which began as a way to reconstruct ancient climate, evolved into investigating ancient human diet and mobility, and more recently entered zooarchaeology and conservation biology. The second is animal genetics, which has revolutionized the study of plant and animal domestication, and has also been applied to understanding ancient foragers' relations with wild species. The third is use of zooarchaeology in the conservation and management of animal species.

Both isotopic and genetic materials can be considered to be strong proxies for specific processes in the past. Certainly, isotopic "signatures" are checked for the effects of situationally variable causes of sample contamination. However, such possible chemical influences on isotopic ratios are *understood* within a systematic causal framework. Likewise, archaeogeneticists' concern with specimen contamination with modern DNA stems from understanding of the biomolecular processes by which the proxy is related to the object of investigation. The next sections outline principles of these methods and offer examples of their applications.

23.1 Bone Stable Isotopes, Diet, Mobility

Isotopes are variants of an element that have the same numbers of protons but differing numbers of neutrons, and hence different atomic masses (Sulzman 2007). Stable isotopes are non-radioactive variants, for example, ^{12}C and ^{13}C versus radioactive ^{14}C. These generally behave similarly in forming molecules and compounds with other elements, but they do display subtle divergences in how they function in chemical processes according to their differences in atomic mass. These subtle divergences in isotope uptake during geochemical, meteorological, and physiological processes form the basis of stable isotope analysis. Pioneering research used the ratios of stable oxygen isotopes ^{18}O to ^{16}O to investigate long-term changes

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in ocean temperatures and, by extension, global paleoclimate (Emiliani 1958; Shackleton 1967, 1968). Shells of Foraminifera, protozoan plankton that grow calcium carbonate ($CaCO_3$) exoskeletons, preserve the oxygen isotope ratios in the seawater surrounding them when they build their shells. Researchers found variations in the ratio of ^{18}O to ^{16}O (the most common stable isotope) in foram shells from deep sea cores, when compared to a modern ocean water standard. Shackleton (1967) detailed the relationship of the proxy to its context of production: the varying ratios reflected the differentially greater uptake of lighter ^{16}O over ^{18}O via evaporation from the sea and other waters and its precipitation into ice sheets, where it was sequestered during glacial maxima, leaving proportionately more ^{18}O in the oceans where the forams were building their shells. Thus, relatively less ^{16}O in the $^{18}O/^{16}O$ ratio in foram shells would reflect colder, glacial conditions, whereas relatively more would reflect warmer seawater conditions. Systematic coring of marine sediments and glacial ice, radiometric and geomagnetic reversal chronology, and analysis oxygen isotope ratios has enabled a chronology of global climate change millions of years long (see Wright 2000 for Marine Isotope Stages).

In the 1970s, advances in mass spectrometry combined with findings on stable carbon isotope ratios in major plant groups to provide new insights into ancient human diet. Archaeologist and geochemist van der Merwe proposed that the prehistoric introduction of cultivated maize, a tropical grass with a distinctive carbon isotope ratio, into temperate North America should produce a shift in carbon isotope ratio "signatures" in the bones of people who up to that time had consumed mainly temperate woodland products. Diachronic analyses of cemetery populations from the Midwest confirmed a shift in $\delta^{13}C$ values – and hence diet – about the time archaeobotanical evidence indicated the introduction of maize (van der Merwe and Vogel 1978).

This led to a proliferation of carbon and nitrogen isotopic analyses of human bones from many temporal and geographic settings (Lee-Thorp et al. 1989, 1994; Ambrose and DeNiro 1986; Lambert et al. 1979; Schoeninger 1979; Schwarcz et al. 1985; Tauber 1981; Walker and DeNiro 1989), as well as refinement of the technique. Bone is more liable to chemical alteration by diagenetic processes Chap. 16), and dental enamel is preferred (Koch 2007). Initially, one sample per individual was considered the norm. However, researchers later began exploring the possibilities of constructing individuals' "osteobiographies." This approach juxtaposes isotopic analysis of teeth and bone with data on deciduous and permanent tooth formation with different bone tissue turnover rates – ribs, for example, replace bone tissue more quickly than do femora – to sample across the body, charting changes in diet and place of residence from childhood through a few years before an individual's death (Sealy et al. 1995; Schroeder et al. 2009).

Stable isotope ratios are measured as R, where R is the heavy/light isotope ratio for a particular element, against the R of a standard reference sample for the element, times 1000.

$$\delta(‰) = ((R_{\text{sample}}/R_{\text{standard}}) - 1) \times 1000$$

This ratio is written ‰, or "parts per mil."

23.1.1 Carbon Isotope Analysis

Like radioactive radiocarbon (^{14}C), stable carbon isotopes enter plant tissues from atmospheric CO_2 through photosynthesis, then moving into tissues of herbivores and ultimately to carnivores (Koch 2007). Carbon-12 (^{12}C) is the most common (98.9% of stable carbon) stable carbon isotope; ^{13}C comprises 1.1% of stable carbon. Carbon isotope dietary research is based on the recognition that three major groups of terrestrial plants fix carbon into their tissues differently during photosynthesis, in the process incorporating divergent proportions of the two stable carbon isotopes (O'Leary 1981). The C3 physiological pathway includes trees, shrubs, and temperate grasses and is thought to be ancestral to the C4 photosynthetic pathway (Ehleringer and Monson 1993). C4 plants are primarily tropical grasses. The third photosynthetic pathway, the CAM (Crassulacean Acid Metabolism), is typical of succulent plants.

The first step of building plant tissue in the C3 (Calvin-Benson cycle) photosynthetic pathway gives the pathway its name. Atmospheric carbon dioxide is taken in by the plant and fixed, via reaction with a catalyst, into phosphoglyceric acid, a *three-carbon* acid. The first step of the C4 (Hatch-Slack cycle) chemical uptake of atmospheric CO_2, results in oxaloacetate, a *four-carbon* acid (Ehleringer and Monson 1993). In physical and biological reactions involving atmospheric carbon dioxide, a bias against uptake of heavier $^{13}CO_2$ molecules plays out because this molecule has slightly stronger chemical bonds than do $^{12}CO_2$ molecules (O'Leary 1981). This disproportionate uptake of stable isotopes, relative to their abundances in a source – in this case the air – is called *fractionation*. Plants using the C3 pathway discriminate relatively more against ^{13}C, resulting in tissues with proportionately less ^{13}C, than do C4 plants. Thus, C3 plants have less ^{13}C in their issues than do C4 plants, which in turn affects their stable carbon isotope ratios. C3 plants have $\delta^{13}C$ values averaging −28‰, while C4 $\delta^{13}C$ values average −13‰. CAM photosynthesis somewhat resembles that of C4 plants, but, because these plants are seldom part of the human food chain, these will not be detailed here (see O'Leary 1981 for details; Ehleringer and Monson 1993). Persons working with human dietary reconstructions in areas known for consumption of cactus leaves and fruit should be aware of the effects of CAM foods on isotopic signals. The standard for $^{13}C/^{12}C$ ratio was Carolina PeeDee Belemnite, which is now exhausted, so the Vienna-PDB is used instead (Koch 2007).

For stable carbon isotopes, the calculated ratio is written as $\delta^{13}C$. As a proxy for plant diet, $\delta^{13}C$ is clearly defined because the pathways of carbon isotopes in plants are well understood, as well as are the processes that transfer plant food carbon isotopes into tissues of primary and secondary animal consumers, or through the longer trophic chains of marine consumers, which are also relatively well understood (Koch 2007). Primary producers in marine environments vary in their concentrations of ^{12}C and ^{13}C, depending upon the overall productivity of the marine environment, on the specific ocean current regime, and on their location in the nearshore–offshore spectrum (Koch 2007). If these factors can be controlled, the locations of primary, secondary, etc. consumers' foraging relative to land masses can be reconstructed (Clementz and Koch 2001).

In human dietary analysis, as with analysis of any omnivore's diet, the signal becomes somewhat more ambiguous, because each food provides its own carbon ratios, and proportionate inputs from different foods can vary. An extensive literature now exists on how best to deal with admixture of foods in the diet (e.g. Newsome et al. 2004; Pilot et al. 2012). Carbon isotope ratios have been shown to fractionate up trophic levels but only about 1‰ in bone collagen with each trophic level (DeNiro and Epstein 1978; Schoeninger 1985). This increment is too small to be accurately used to evaluate consumers' trophic levels, however, nitrogen isotopes can be used to do so.

23.1.2 Nitrogen Isotope Analysis

Proportions of stable nitrogen isotopes, ^{15}N and ^{14}N, have been used to specify animal food inputs and terrestrial versus marine foods (Sealy and van der Merwe 1988; Schoeninger and DeNiro 1983; Schoeninger and Peebles 1981; Walker and DeNiro 1989). Nitrogen enters the food chain at the level of plant primary producers, which obtain it from the soil in which they grow. Levels of nitrogen, especially ^{15}N, vary with overall soil chemistry, as well as with the presence of nitrogen-fixing plants, such as legumes, and their bacterial symbionts. Therefore, local baseline values must be obtained for local terrestrial environments. Nitrogen enters primary producers in marine environments via a different pathway, which produces a distinctive $\delta^{15}N$ marine signature.

Animals obtain nitrogen almost exclusively from the protein they ingest. The proteins are then broken down into amino acids, complex molecules that include carbon, oxygen, and hydrogen (carboxyl groups) bonded with nitrogen and hydrogen units (amino groups), as well as "side chains" of carbon and hydrogen. Animals' physiological breakdown of proteins and use of amino acids differentially fractionates the two nitrogen isotopes. In this case, fractionation in animal tissues takes up more of the lighter ^{14}N isotope than the heavier ^{15}N, the lighter isotope being differentially excreted in urea. This process enriches the proportion of ^{15}N in an organism's tissues, compared to that in its protein intake. As the proportion of ^{15}N in the body consistently increases, $\delta^{15}N$ at each trophic level increases by about 3‰. This permits researchers to assess trophic levels occupied by extinct organisms or the amount of animal protein in an omnivorous organism's diet. In marine ecosystems, a latitudinal gradient in nitrogen isotopes at the level of primary production also exists, which permits estimation of the latitude where an animal foraged, if other parameters can be controlled. Animal species with high-protein diets use amino acids and the nitrogen they contain differently than do animals with low-protein diets (Koch 2007). Therefore, some knowledge of the actual physiological linkages of this proxy in "target" species is necessary.

Nursing mammals display a $\delta^{15}N$ isotopic signature 3‰ above that of their lactating mothers, given that they are literally consuming her tissues, in the form of breastmilk. Biological anthropologists interested in the weaning ages of different

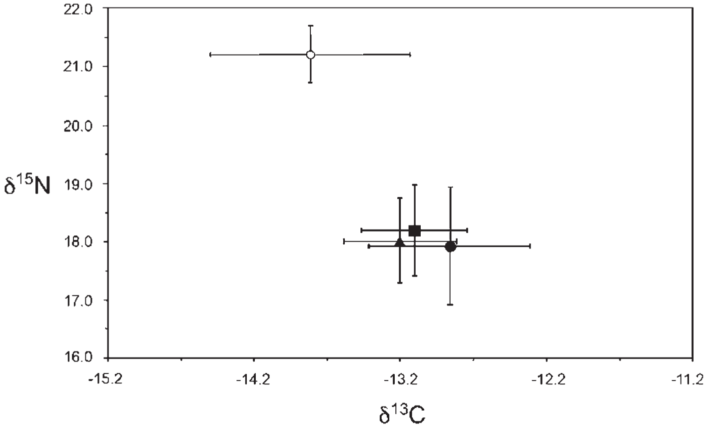

Fig. 23.1 δ15N plotted against δ13C values for northern fur seal (*Callorhinus ursinus*) specimens recovered from CA-MNT-234, the Moss Landing Hill Site showing nursing pups (open circles) are 3‰ higher in δ15N than are adult females (closed squares). Also depicted are juveniles a little over a year old (closed circles) and older subadults (closed triangles). (Redrawn by the author from Burton et al. (2001:111, Fig. 1), with permission of the R. Burton and Springer)

human populations and pre-modern hominins have analyzed $\delta^{15}N$ isotopic signatures of teeth that typically develop during early childhood (Richards et al. 2009; Oelze et al. 2011). Using the same analyses zooarchaeologists have examine livestock (Balasse and Tresset 2002) or other species' weaning patterns (Newsome et al. 2007, Fig. 23.1).

Analyses of human bones have combined stable carbon and nitrogen isotope analysis in surveying cemetery samples to assess whether elite versus lower-ranking individuals had different diets, as has Gerry (1997) with elite versus commoner diet among the Classic Maya (see also White and Schwarcz 1989) and Ambrose et al. (2003) with diets of those interred in Mound 72 at the Mississippian metropolis of Cahokia. At Cahokia, researchers saw clear gender differences in estimated proportions of maize to animal inputs in diet according to gender, and presumably, the rank of the individuals.

23.1.3 Oxygen Isotope Analysis

The standard for oxygen isotopes is a global O^{18}/O^{16}ratio, the Vienna Standard Mean Ocean Water (the Vienna Pee Dee Belemnite limestone is also used). More positive fractional ratios have proportionately more of the heavier and rarer isotope, while those more negative ratios have proportionately more of the lighter and more common isotope. For a clear summary of the actual technological analysis by which samples are assayed for their isotopic ratios, see Sulzman (2007). The same oxygen isotopes used in marine paleoclimate research have been used in different contexts, albeit with some complications, to characterize dietary intake, climate, seasonality, and, by extension migration to habitats characterized by different $\delta^{18}O$ regimes. In purely geological-meteorological systems, processes of isotopic fractionation are well understood, with evaporation leaving relatively more ^{18}O than ^{16}O behind in the evaporating water, although the water vapor in clouds does contain another, relatively predictable amount of ^{18}O in its molecules (Gat 1996). *Meteoric water*, that is, water deriving from precipitation, can vary in $\delta^{18}O$ values, depending upon a complex set of interactions: the initial condensation of water vapor into precipitation favors heavier water molecules, so that the first rain, snow, or sleet to fall is relatively enriched in ^{18}O, while later precipitation in the same event is isotopically lighter. Rainfall patterns are not random and somewhat predictable: land, especially mountains, close to the first landfalls of water-rich air masses moving in from large bodies of water will, by virtue of their lower temperatures, provoke condensation and precipitation, whereas zones farther inland will receive less, and relatively isotopically lighter, precipitation (Gat 1996). Thus, it is possible to predict to some degree where isotopically heavier versus lighter precipitation is likely to fall. Seasonal variations are also relatively clearly reflected in $\delta^{18}O$ values of precipitation collected at weather stations, and researchers have identified at least some of the major drivers of these variations in the marine evaporative and precipitation cycles (Gat 1996).

Notwithstanding these variations in the $\delta^{18}O$ composition of precipitation (see Gat 1996 for more details), by virtue of its evaporative origins, meteoric water is generally lighter in ^{18}O than is seawater. Gat (1996) points out that ^{18}O enrichment of meteoric water can occur if it travels through dissolvable bedrock enriched in that isotope, such as phosphate-rich rocks. Meteoric water in lakes where evaporative processes have outpaced fresh meteoric inputs will display heavier $\delta^{18}O$ values, as more ^{18}O is "left behind" in the unevaporated water. However, all of these geological and meteorological processes are stable enough that $\delta^{18}O$ ratios can be used to monitor past variations in cooler/moister versus warmer/drier phases in geological history (e.g. Ricketts and Johnson 1996). In other words, the functional linkages between the "target" of interest and the proxy are reasonably well understood.

When oxygen isotopes are taken into animal tissues, an additional fractionation is added. Oxygen isotopes are taken up into bioapatite phosphate, as well as carbonate and calcium carbonate, all of which derive from body fluid (Koch 2007). Experimental observations have stipulated some of the sources of variation. Oxygen isotope fractionation in homeothermic mammals' phosphates in bioapatites remain consistent at about 18‰, while that in carbonates in bioapatite is lower 8‰ (Koch 2007). Thus, the *physiological* aspect of isotopic uptake of environmental oxygen isotopes in mammal bodies is relatively well understood. As with other isotopic signatures in vertebrates, dental enamel is the most stable record of ambient conditions.

The proportionate transfers of oxygen isotopes into the mammalian body depend on the sources of $\delta^{18}O$. Over half of oxygen uptake by terrestrial mammals is through drinking water and the water in foods, and no fractionation occurs during uptake. Inhalation of atmospheric oxygen and water vapor during respiration does result in fractionation, with differential uptake of ^{16}O, while exhalation, sweating, and excretion take oxygen from the body, with the first two fractionating in favor of loss of ^{16}O (Koch 2007). Meteoric water is the main source of drinking water most modern mammals, and, as noted above, δ^{18}O values will be expected to vary geographically and seasonally. The larger the body of fresh water from which they drink, the less seasonal variation will be recorded in δ^{18}O values. Thus, archaeologists interested in using δ^{18}O values to reflect seasonality must know a good deal of the physical geography and hydrology of the target region.

Finally, the habitual dietary water sources of herbivore species will affect δ^{18}O values. Leaf water δ^{18}O values are higher in C3 plants than in C4 plants, and among C3 plants, higher in dicot plants than in grasses (Koch 2007). This means that interspecies variations in browsing versus grazing habits of the primary consumers (herbivores) may be considerable. Prudent studies of seasonality based on δ^{18}O therefore focus on a single species within a restricted region, where drinking and plant sources of water can be controlled, as was the case with studies by Balasse et al. (2003).

Given all these considerations, oxygen isotopic analysis of terrestrial vertebrate remains best proceeds with a thorough understanding and explicit description of the boundary conditions for its application within the geographic, temperature, precipitation, forage and other influences on the samples under study.

In an application of oxygen isotope analysis to humans, White et al. (2002) used δ^{18}O in dental enamel to explore the regions of origin of persons exhumed from under the Temple of the Feathered Serpent in Teotihuacán's Citadel area. Their analysis built upon known δ^{18}O values for bioarchaeological dental enamel in humid lowland regions of Mesoamerica, which display relatively lower δ^{18}O values, in comparison to relatively higher δ^{18}O values in persons from the drier highlands, including ancient inhabitants of Monte Albán and Teotihuacán. White et al. found that most warriors, so identified from their body decorations and associated weaponry, interred in the mass inhumation had formed their teeth in humid lowlands and moved to Teotihuacán as adults. By contrast, most of the women put into the mass burials displayed local δ^{18}O values, reflecting their having lived in or near Teotihuacán their entire lives. Male individuals from the central part of the temple, assumed to be high-ranking personages, were much more variable in their personal histories of mobility.

23.1.4 Isotope Analysis and Zooarchaeology

Isotopic analysis of human tissues can reveal what a person actually ate, in contrast to the coarser resolution supplied by archaeofaunal and archaeobotanical evidence available at a site, but which may not have been equally accessible to all. One may well ask, why go to all the trouble of zooarchaeological analysis, if we can just find out what people ate by analyzing their bone chemistry? Amidst sorting a 10,000-specimen faunal assemblage, this question may seem particularly compelling. Some good reasons exist why isotopic analysis does not supersede zooarchaeological analysis. Most importantly, human skeletons are not that readily encountered nor used for stable isotope analysis. Not all archaeological sites that yield faunal remains also have burials. Not all burials can be used for isotopic analysis: descendant communities may be in the position to ban the destructive analysis involved in isotopic research, if they believe that it treats ancestral remains disrespectfully. Although bone isotope analysis can reveal, for example, proportions of terrestrial and marine animal foods in the diet, it cannot specify the species actually taken and processed. Finally, isotopic studies cannot shed much light on the handling of animal bodies prior to their death or after. Only zooarchaeological analysis of pathologies, bone modifications, and refuse disposal practices can elucidate these topics.

Ideally, archaeofaunal data can be read in a dialogue with the bone isotope data, to ask if there are radical departures from expectations generated by one dataset in the results of the other. Zooarchaeologists may note varying taxa in different houses' trash, but seldom can determine the extent to which social or economic barriers restricted members of specific social or gender classes from regularly consuming animal products or plant products they processed, but bone isotope analysis can do so. Stable isotope analysis of *archaeofaunal* samples has proliferated as a normal practice in zooarchaeology, and only a few cases will be discussed here. Noe-Nygaard (1988) assayed isotopic composition of domestic dog bones from Danish sites spanning the transition from Mesolithic hunting-gathering subsistence to food-production. Because of dogs' commensal relation with humans, she used them as proxies for human diet, in effect substituting for human bone not recovered from the middens. Stable isotope ratios in dog bones changed diachronically, reflecting subtle dietary shifts in the transition to domesticates not definitively indicated by other evidence. White et al. (2001) examined dog and deer bone isotopes from refuse at the Classic Maya site of Colha. Results showed that dogs ate a predominantly C4 pathway plant food diet (probably maize), reflecting both their intimate dependence on human provisioning, and, since most died at about 1 year of age, that they seem to have been raised as a meat source. By contrast, deer bones from Colha reflected a C3 pathway diet, typical of deer's natural wild browsing. Later research distinguished a few deer at other Maya sites that appear to have been heavily provisioned with maize or that were set to feed heavily on cultivated land, perhaps in preparation for religious ritual in which they were sacrificed (White et al. 2004).

A research group of which I was a member used bone stable isotope ($\delta^{13}C$, $\delta^{15}N$) analysis to explore why northern fur seal (*Callorhinus ursinus*) remains were common in central coastal California sites up to about a thousand years ago, then vanish from the region's archaeological record. Many present-day female *Callorhinus* forage about 8 months year at middle latitudes off Oregon and California, never coming ashore unless ill or injured. They go north to breed in the Pribilofs and Siberian islands, where they feed offshore for the 4 to 6 months they nurse their young. Though most *Callorhinus* today follow this pattern, in 1968, the species re-established a breeding colony on San Miguel Island, off Santa Barbara, California, having been wiped out there by commercial sealing in the 1800s (Peterson et al. 1968). In the early twenty-first century, fur seals re-established a breeding colony on South Farallon Island, due west of California's Golden Gate, where they had been extirpated in the 1820s (Pyle et al. 2001; Martin 2006).

Using modern stable carbon isotopes from reference samples of modern fur seals and near-shore foraging harbor seals (*Phoca vitulina*), Koch and Burton established that archaeofaunal fur seals displayed an offshore carbon signature, and like modern conspecifics, they foraged far from land (Newsome et al. 2007). Koch and Burton also sampled harbor seal and California sea lion (*Zalophus californianus*) museum specimens from points between Alaska to Mexico to assess whether pinniped $\delta^{15}N$ values reflected foraging latitude, establishing that isotopic variation exists (Burton et al. 2002). Female archaeofaunal specimens showed divergent $\delta^{15}N$ values from those of modern, Pribilof-breeding females, with values closer to those of Miguel Island females, which do not feed or breed in the far north Pacific. The $\delta^{15}N$ values implied that the archaeological females from central Californian coastal sites came ashore to breed in the region, placing them and their pups at risk of predation by hunters. Measurements of central Californian *Callorhinus* young-of-the-year suggested these were below weaning age (Etnier 2002), which was confirmed by their 3‰ enrichment of $\delta^{15}N$ above maternal values (Fig. 23.1). Newsome and Etnier expanded isotopic studies of archaeofaunal *Callorhinus* samples to far northern California, Oregon, Washington, British Columbia, and Alaska, where northern fur seals were present later than in central California. Isotope values suggested the past existence of two fur seal populations, one foraging and breeding along the California and Oregon coast, and one circulating north from the Olympic Peninsula with multiple breeding sites south of the Aleutians (Newsome et al. 2007). A study of the fall-off in 3‰ $\delta^{15}N$ enrichment in weaned young suggested that young at the latter sites were weaned later than do those in the far northern islands do today.

Summing up, stable carbon and nitrogen isotope ratios indicate that northern fur seals formerly had a different biogeography ago than in any historically recorded time, and that something changed around a millennium ago for animals along the coast of California. Explanatory hypotheses for this shift include human overcropping (Whitaker and Hildebrandt 2011), effects around the time of the Medieval Climatic Anomaly, when California was subject to prolonged drought (Jones et al. 1999), or termination of the mid-Holocene Neoglacial and reopening of the higher-productivity Bering Sea for breeding colonies (Crockford and Frederick 2011; Gifford-Gonzalez 2011).

23.2 Genomics, Domestication, Biogeography

While not without its own interpretive controversies (see Marshall et al. 2014), genomic analysis offers another strong set of proxies to zooarchaeologists investigating the evolutionary and biogeographical history of wild or domestic species. DNA analysis has greatly improved zooarchaeological research on actual genetic affinities of morphologically similar species, patterns of intraspecific population replacement from past to present in various regions, and animal domestication. Before examining applications of genomics to zooarchaeologically relevant questions, a review of basic terms, processes, and analytic approaches is useful.

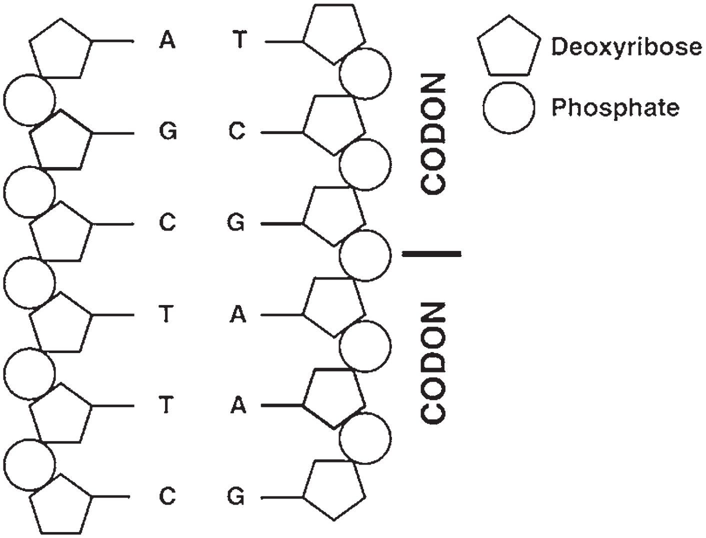

Fig. 23.2 DNA strand, showing an "unzipped" double row of nucleotide bases and the possible pairings of the bases and two three-base pair codons. The nucleotide bases consist of a deoxyribose sugar, phosphate, and a nitrogenous base. Key: A-adenine; T-thymine; G-guanine; C-cytosine. The first two only bond with each other, as do the second two (From Campana et al. (2013):24, Fig. 1). Used with permission of the D. Campana and Springer)

23.2.1 Terms, Processes, and Analyses

The famous "double helix" of DNA, or deoxyribonucleic acid, is made up of made four nucleotide bases, each comprising a deoxyribose sugar and a phosphate, plus a nitrogenous base. In DNA, these four nucleotide bases are cytosine, guanine, adenine, and thymine, abbreviated as C, G, A, and T, respectively (Fig. 23.2). Each of these bases bonds with only one of the others, forming "bridges" between the two spiraling strands of the double helix: adenine bonds with thymine, and guanine bonds with cytosine (Hartwell 2011). Eukaryote cells, including those of mammals, have a nucleus, which contains the DNA (*nuclear* or *nDNA*) comprising most of the DNA in the organism. Nuclear DNA contains the codes, three base pair units called *codons*, which direct specific amino acid and protein synthesis, building living tissue and determining its function. These are flanked by "start" and "stop" codes that regulate the syntheses (Matisoo-Smith and Horsburgh 2012). Some codons are promotor regions, which regulate lower-order tissue synthesis and function (Hartwell 2011). Much nuclear DNA seems to serve neither function and is often called "junk DNA," although this term may reveal more of our ignorance of gene function than the non-functional role of these codons. Nuclear DNA is considered to be the focus of selection, and mutations at the regulatory level are seen as key to the rapid morphological changes seen during domestication (Zeder et al. 2006). Nuclear DNA is "packaged" into dense bodies called chromosomes, which, except for the X and Y sex chromosomes, exist in pairs (homologous chromosomes), one derived from each parent. Numbers of chromosome pairs vary with species.

Nuclear DNA replicates itself with ribonucleic acid as messenger RNA (mRNA), via *transcription,* in the process traditionally called *mitosis*. In transcription, the double helix unzips the bonds between the bases, and RNA builds on the open bonds with the same bases, except that uracil substitutes for thymine. Transcription produces the mRNA copy of the gene replicated, which then structures the assembly of new amino acids in the order of the original DNA, in a process known as *translation*. Translation is facilitated by ribosomes in the cell's cytoplasm and another form of RNA, ribosomal RNA (rRNA). In contrast to one-celled organisms, eukaryote translation is more complex because cell walls separate the nuclear DNA from the ribosomal bodies that synthesize the proteins coded by mDNA (Hartwell 2011). The processes involved are intricate, involving sequences of triggering and dampening chemical reactions. During these multiple steps, errors in transcription or translation can occur, which may produce mutations.

Transcription errors transmitted to later generations are those that occur during *meiosis*, the unique process leading to specialized sex cells called *gametes*, the sperm and ova. In meiosis, the cell nucleus first divides in two, somewhat like with mitotic division, producing two cells with the full (diploid) complement of chromosomes in their nuclei. In contrast to mitosis, the two daughter cells divide again, partitioning halves of each homologous chromosome pair into separate nuclei and cells containing half the normal complement of chromosomes, the *haploid* condition. Genetic diversity can emerge two ways during the initial phase of meiosis. First, *crossing-over* can occur, as a section of one parent's homologous chromosome swaps with the corresponding section of the other parent's chromosome. This *recombination* produces a novel set of codons on each chromosome. Second, nonhomologous chromosomes sort independently of one another, that is, a single daughter cell can include some halves of chromosomes pairs from the mother and other halves from the father. With the second cell division into four haploid cells, one gamete could thus include some maternal and some paternal chromosomes.

Another type of DNA important in genetic research is located outside the eukaryote cell nucleus, in mitochondria. This is referred to as mitochondrial DNA or *mtDNA*. While passed from a mother to both her male and female offspring, it is only transmitted through the female line. Mitochondria are quite numerous in most eukaryotes' extra-nuclear cytoplasm and have been called the powerhouses of the cell, because they use glucose to produce adenosine triphosphate (ATP), the energy source for cell activity. They are considered *endosymbionts*, having originated as independent aerobic bacteria that were engulfed by early cells with nuclei (Hartwell 2011). DNA of a single mitochondrion replicates itself in a way more like that of one-celled organisms and is highly diverse. Mitochondrial DNA is not thought to be directly under selection, a trait that makes it advantageous to use in studies of evolution (Bruford et al. 2003). In mammals, the control region of the mtDNA's roughly circular, D-loop mutates more swiftly than does nuclear DNA, which allows the relatively short-term evolutionary changes on the scale of mammal domestication to be monitored. Analyses of mtDNA initially used segments of the D-loop, but whole-genome of mtDNA analysis is now possible.

Several terms commonly used in genomic analysis also require definition. A *single-nucleotide polymorphism* (SNP) is a codon in which one of three base pairs – G-C, C-G, A-T, T-A – differs from codons of other members of the same species. It is the simplest form of polymorphism. It may code for different amino synthesis, but most SNPs have no such effect. They are useful in tracing relationships of common descent and differentiation (Hartwell 2011).

A *haplotype* is a string of related codons at a specific place, or locus, on a single homologous chromosome that function as a "gene," that is, they code for a specific protein or function. They can be as small as a one locus, single-nucleotide polymorphism (SNP), or as large as an entire chromosome. Haplotypes are transmitted as units during replication processes. The term is a contraction of "haploid genotype" (Hartwell 2011). A species may have only one haplotype for a trait, or, due to base pair changes, there may be variants for the trait, called *alleles*.

A *haplogroup* (or *clade*) is a group of similar haplotypes that derive from a common ancestor with a single nucleotide polymorphism mutation.

Nuclear *microsatellites*, or tandem repeats, are short sequences of nucleotides that are both paternally and maternally inherited and repeat variable numbers of times in the DNA sequence of base pairs. Over time, these may increase or decrease in number, apparently neutrally with relation to selective forces. They can be distinctive to regional populations and thus are particularly useful in tracing the domesticated animal movements from their regions of origin to other areas.

A *genome* is the sum total of a given species' genetic information. Genomics is the study of all aspects of such information.

Y-chromosome analysis involves comparisons of the diversity in the male sex chromosome, which passes through the father's line. Because the Y-chromosome is nuclear DNA, it is relatively rarely retrieved from ancient tissues. As noted earlier, it is complemented by *mtDNA* analysis to assess similarities, differences, and common descent through the paternal and maternal lines, respectively. This has proved especially useful in tracing introductions of domestic animal males or females into new areas (see next section).

Ancient DNA (*aDNA*) analysis provides insights into animals' genetic diversity in the past, allowing study of now-extinct ancestral populations and sometimes revealing now-extinct branches of extant species. It relies on analysis of genetic material extracted from bones, teeth, or eggshells. Ancient DNA research suffers from several impediments. DNA degrades over time, shortening the lengths of the fragments of recoverable bases, and thereby challenging base pair amplification in the laboratory. Varied environmental conditions, can hasten DNA deterioration, and arid zones are generally unfavorable for DNA preservation (Campana et al. 2013). Various contaminants can enter DNA samples, in both field and the laboratory, including penetration of fungal and bacterial DNA into archaeological specimens in their depositional contexts (Chap. 15) and contamination by modern DNA during retrieval and laboratory preparation.

Ancient DNA analysis relies on *amplification* of genetic materials. Until recently, this involved variants of the *polymerase chain reaction* (PCR) method, developed in the mid-1980s (for a history of this and earlier methods, see Matisoo-Smith and

Horsburgh 2012 or Hartwell 2011). PCR made it possible to isolate small segments of DNA and reproduce numerous copies of them in a gel, using artificial heat cycles to instigate replication and providing the chemical raw materials for the replications. Over time, the PCR process became more intensively automated, but it always required a substantial amount of human labor in the transfer of the original DNA segments to their replication matrix. It has been widely used in forensic investigations, where DNA is often recovered in degraded form, as well as in research on the genetics of disease and the phylogeny of species. PCR allowed researchers to extract degraded DNA from ancient bone or other biological tissues and to determine the genetic sequences present. The first "targets" of such ancient DNA research were shorter nucleotide strands such as SNPs and microsatellites, as these would often be preserved in short lengths of degraded DNA.

By the late twentieth and early twenty-first centuries, laboratories experimented with reliably sequencing and reading entire genomes of common lab organisms such as *Escheria coli*. The Human Genome Project pioneered "high throughput" laboratory instrumentation, with computer programming suited to reading masses of biochemical sequencing output and constructing coherent digital versions of it. In the early 2000s, such sequencing took months of complete, even with entire DNA samples, and was intensive of labor and resources and hence expensive. The high-throughput approach did permit, for example, sequencing the Neanderthal genome (Green et al. 2010). Emergence of a range of next-generation sequencing (NGS) methods in the late 2000s rendered whole-genome sequencing of relatively cheap and reliable (Matisoo-Smith and Horsburgh 2012), and permitted swift study of targeted parts of genomes in biomedical research. NGS techniques involve recovering, labeling, and amplifying DNA on a massive scale, largely automatically after preliminary sample preparation. Some approaches continue to use PCR. Others use newly devised biochemical means of isolating target DNA within much larger assemblages of genetic materials (Koboldt et al. 2013). Presently, many different commercial technologies are available, with high degrees of reliability in controlled tests, but considerable variance in cost. The next few years will doubtless see more standardization in these approaches. Koboldt et al. (2013) stress that NGS methods all rely upon the prior existence of reference sets of species genomes, with which genetic segments can be identified.

23.2.2 Animal Domestication Research in Zooarchaeology

Research on animal domestication has benefited tremendously from the emergence of genomics and a truly global approach to the genetics of modern, economically important species and breeds. Genomic research has focused on domestic species because of their commercial uses, while wild species have been less well studied. Data derived from modern breed research provides insights into early domestication, and aDNA of the same species has refined ideas derived from surviving lineages. This section provides some examples of how genomics has revolutionized zooarchaeological research on domestication.

Formerly, animal domestication was the sole research province of zooarchaeological, and most frequently, European archaeozoological, research. Investigations relied upon osteometrics and distinctive non-metrical morphological traits thought to be distinctive of certain regional populations. However, many problems attended these efforts (Zeder 2001; Zeder and Hesse 2000). Analysis of living domesticates' mtDNA and Y-DNA has produced a clearer picture of where and how many times members of a wild species moved into domestication. Results of this research have prompted rethinking of initial assumptions about domestication processes. For example, domestic animals of any given species were expected to have only one or two mitochondrial lineages. Yet horses, goats, sheep, llamas, and alpacas have multiple maternal lineages, and substantial interbreeding of domestic llamas with alpacas is evident (Naderi et al. 2008; Meadows et al. 2007; Bruford et al. 2003; Barreta et al. 2013).

Multiple mtDNA lineages were initially interpreted as reflecting independent, geographically distinct domestications that later coalesced as agrarian systems expanded. It was more recently proposed that this results from intentional recruitment of wild females into early domestic herds (Marshall et al. 2014), challenging the long-held idea that domestication occurs only under reproductive isolation from wild conspecifics. Marshall et al. also propose that, rather than a one-size-fits all model for domestication, zooarchaeologists and archaeogeneticists must understand how the behavior of specific classes of domesticates affect domestication trajectories, a point also raised by Zeder (2012). Dogs and cats, also displaying multiple mtDNA lineages, may have come to domestication as commensals rather than prey (O'Brien et al. 2008; vonHoldt et al. 2010; Ottoni et al. 2017).

Mitochondrial and Y-chromosome DNA of living domestic breeds and, in fortunate cases, aDNA (thus far, nearly always mtDNA) from archaeofaunal specimens can be used to trace the history of domestication in space, and through time (*phylogeography*). Haplotypes indicate that cats came under domestication twice, once in Southwest Asia around 10,000 years ago and millennia later, in Dynastic Egypt (Ottoni et al. 2017). Ancient DNA has the advantage of revealing lineages of wild or domestic species that no longer exist. For example, aDNA from the palaeolithic dogs noted above showed these were not related to any living dog population. Donkeys comprise two mtDNA lineages, one of which represents the Nubian wild ass and the other an extinct population most like, but not identical to, the Somali wild ass (Kimura et al. 2011).

Genetic evidence can offer insights into livestock management (Marshall et al. 2014). Ottoni et al. (2017) argue that maritime trade in the Classical Mediterranean world, and that between the Roman Empire and South Asia, facilitated the spread of domesticate cats, probably as ship's cats as well as in their more traditional role in farm pest control. DNA analysis significantly revised the history of pig management in Europe. The wild ancestors of domestic pigs were widespread across Eurasia and North Africa, and haplogroups indicate a least six local domestications from regional Asian and European populations (Larson et al. 2005). Pigs were domesticated in the Southwest Asia 13,000–15,000 years ago and were introduced to Europe as part of the "Neolithic package" of domesticates. Archaeologists initially assumed European domestic swine descended from this stock, but modern European domestic pigs uniformly lack Southwest Asian haplotypes, instead bearing those of native European boar . Archaeogenetics shed light on this issue: the oldest, sixth-fifth millennium BC domestic pig specimens in Europe display only Southwest Asian haplotypes (Larson et al. 2007). However, a millennium later, some specimens testify to emergence of indigenous domestic pig stock alongside imported swine (Larson et al. 2007). By the mid-fourth millennium BC, all European domestic swine sampled display European haplotypes, suggesting that European stock increased from around 5% to 100% in less than 500 years. This may suggest European pigs' greater fitness in their ancestors' native environments, but their rapid spread from the British Isles to Eastern Europe also reflects human interaction at a continental scale. Thus, genomics of domestic animals and plants can be a reasonable proxy for human interaction and exchange.

23.2.3 Applications of DNA Analysis to Wild Species

The use of wild species has also been explored with aDNA analysis. Salmon aDNA from archaeological sites along the Northwest Pacific coast was able to identify species with greater accuracy than did zooarchaeological analysis across a range of sites (Cannon et al. 2011). Cannon and Yang (2006) combined aDNA analysis with the archaeology of Namu, a long-occupied village facing the Inside Channel. Based on archaeological evidence for salmon storage plus aDNA evidence for dominant use of pink salmon (*Oncorhynchus gorbuscha*), they argued that occupational disruption may have been due to interruptions in the abundance pink salmon in the region. Speller et al. (2012) used SNP's in aDNA to explore the hypothesis that ancient herring populations in the British Columbia region were more regionally specific than recent ones subject to heavy harvesting, finding no demonstrable differences from modern populations.

Our investigation of ancient fur seal biogeography and feeding ecology showed via archaeofaunal evidence that *Callorhinus* was once more densely distributed from San Miguel Island to Unalaska Island, and, via stable carbon and nitrogen isotope analyses, that a northern and a southern foraging population existed at that time. We asked Malin Pinsky, from Liz Hadley's Stanford University aDNA laboratory to explore whether ancient northern fur seals were of a different genetic stock than modern ones, and if the northern and southern foraging groups were genetically distinct. aDNA results indicated that, like their modern relatives, archaeofaunal *Callorhinus* were part of one, heterogeneous pool of haplotypes ranging from the far north to the far south of their ranges, without geographic distinctions (Newsome et al. 2007). Individual tagged *Callorhinus* have shifted breeding sites from Pribilof and Siberian Islands to the Santa Barbara Channel and Farallon Islands. Pinsky et al. (2010) argued that the great dispersal abilities of these marine mammals have probably contributed to the species' resilience in the face of heavy local extirpation over the last few centuries. This research leads into the final topic discussed in this chapter, zooarchaeology as it can be applied to species conservation.

23.3 Zooarchaeology and Conservation

"Applied zooarchaeology" (Lyman 1996) aims to support conservation biologists in managing endangered or economically valuable taxa, by synthesizing and conveying data on species ancient biogeography and population dynamics. It emerged in the 1990s as a practical means to contribute to the field of *historical ecology*, which studies human interactions with species and landscapes over time, using all types and scales of evidence, from written documents and photographs to geological and climatic data. Jackson et al. (2001) noted that written records cover a few thousand years, and usually much less, and, to understand evolution and ecology of species with which humans have interacted for millennia, only archaeological and paleontological records offer relevant records. Several excellent sources on applied zooarchaeology exist. Lauwerier and Plug's *The future of the past: Archaeozoology in wildlife conservation and heritage management* (2004) provides a global perspective on similar matters. Lyman and Cannon's *Zooarchaeology and conservation biology* (2004) and Wolverton and Lyman's *Conservation biology and applied zooarchaeology* (2012a) offer thoughtful contextualizing analyses of the field's challenges as well as a range of case studies.

This section reviews basic themes in applied zooarchaeology, with examples from the literature and my own research experience. While applied zooarchaeology seems a worthy way of making zooarchaeology relevant to present-day problems, three issues face zooarchaeologists who wish to use archaeofaunal data in this way. One is largely methodological, another theoretical, and the last and most critical is sociopolitical. As will be seen, these issues blend into one another, so that that all communications between zooarchaeologists and conservation biologists are imbued with more political aspects than the former may initially assume.

Some definitions are useful at the outset. First, I follow Wolverton and Lyman's (2012a) use of the term *conservation biologist* to refer to persons who manage wild species or habitats. As outlined in Lyman and Cannon's introduction (2004), this group actually includes the more senior generation of "wildlife managers," who worked to conserve species that were valued economically or aesthetically, and who executed their tasks largely without recourse to an ecosystems approach. More recently credentialed conservation biologists tend to view their role as applying ecosystems-based approaches to management of species under threat from economic exploitation, pollution, and other factors. Lyman and Cannon point out that, the more interest managers have in species' long-term adaptation and ecological history, the more relevant zooarchaeological data are to them. However, as Reitz and Wing (2008:331–334) note, the differences between archaeofaunal datasets and those to which conservation biologists are accustomed require some mutual education and negotiation of expectations.

23.3.1 Requisites for Effective Applied Zooarchaeology

To give conservation biologists the information they need requires regional-scale data, drawn from multiple, well-dated and well-recovered sites. Reitz and Wing (2008:316–334) offer a nuanced discussion of a range of methodological and interpretive issues to be considered when producing reliable information for conservation biologists, as well as offering insights into why applied zooarchaeology emerged relatively late in the history of the field. Zooarchaeologists must also apply rigorous standards when assessing historical documents regarding species of interest in the region. Applied zooarchaeologists thus judiciously abstract and synthesize from ecological, historical, and archaeological literatures as well as from their own research findings.

Another major consideration is how well certain archaeofaunal samples were recovered, especially if one is dealing with smaller taxa, such as fishes, birds, and smaller mammals (e.g. Butler and Delacorte 2004; Grayson 2011). If ¼” mesh was used to screen site materials for animal remains, one’s ability to tell managers about the presence, absence, or relative abundances of small taxa is compromised (Chap. 8). Some well-recovered archaeofaunas from a region could be used in conjunction with less well-recovered ones from the same regions, to provide general outlines of species representation, as has been the intention of the Arizona State Museum’s FaunaAZ database (Pavao-Zuckerman et al. 2006).

Regional samples can be used to tell conservation biologists whether a species that is not present in a region now existed there earlier, when it did, and with some informed opinions on climatic or human impacts with which its disappearance coincided. Stable isotopic analysis can shed light on whether individuals of a species moved considerable distances during their lifetimes, or whether their diets diverged from what is known to characterize the modern species. With well-recovered archaeofaunal samples, or with coordinated aDNA data, zooarchaeologists might be able to offer an opinion on whether the species was abundant in an area. For some species, zooarchaeologists might use mortality profiles or presence of young-of-the-year to assess whether the species bred in the region.

A few cases can illustrate these applications. After decades of controlled sampling of Great Basin microfauna and critical synthesis of radiometric dates from many sites, Grayson (2011) could chart the fortunes of two lagomorph species, the alpine pica (*Ochotona princeps*) and big sagebrush-adapted pygmy rabbit (*Brachylagus idahoensis*), as well as various rodent taxa closely associated with specific vegetation communities. He was thus able to track a range of temperature and humidity regimes at different altitudes and various regions of the Great Basin since the Last Glacial Maximum to historic times. Grayson supplemented and contextualized his voluminous archaeofaunal data with supplemental environmental records from published pollen spectra, dated macrobotanicals from packrat middens, and other sources. Tracking the biogeography of these microfaunal species, along with larger taxa, including deer, antelope, and bison, through changing climate and patterns of human land use, Grayson (2011) was able to comment with substantial empirical support on present-day management issues. This included his inference that decline in sagebrush, widely attributed to historic overgrazing by introduced domesticates, was in fact already underway before the arrival of Euro-Americans.

Bovy (2012) used historic records and archaeofaunal remains of sandhill crane (*Grus canadensis*) to argue that early historic observations of dense aggregations of the cranes on the Strait of Juan de Fuca (northwestern Washington State) actually were breeding colonies. She placed her research findings the context of current management issues regarding the species. Rosania (2012) used bone stable isotopes to compare the diets of modern black bears (*Ursus americanus*), which are extending their range from the state of Arkansas into Missouri, where the species was extirpated in historic times. With black bear specimens recovered from a pre-Contact Missouri cave, she found no isotopic differences between ancient and modern bear diets in the same region. Crowley et al. (2012) used intensive radiocarbon dating and stable isotopic analysis to track the patterns of extinction of Madagascar mega-lemurs in the last 2000 years, coinciding with human colonization of the island. Among their most interesting findings is that all lemurs, including surviving ones, lived in more arid environments than those set aside as reserves for these threatened species, with management implications for sustainability of these populations.

23.3.2 Defining the Target Baseline: A Collaborative Exercise

The second major issue in applied zooarchaeology is that of the target state to which managers wish to restore ecosystems and the species within them. Most can agree that the desired state is one that existed before degradation by over-exploitation, agricultural practices, invasive non-native species, and other forms of habitat destruction. But what – and when – should that target "baseline" be, and how can zooarchaeologists collaborate in deciding this? In the Americas and Africa, for example, it is becoming increasingly clear that native peoples managed landscapes more intensively than previously assumed by biologists and ecologists. In California, for example, the open, flower-rich grasslands praised by such naturalists as John Muir may largely have been created and maintained by Native Californians, who used repeated, small-scale burning to maintain the vegetational succession at stages most useful to them for food and basketry materials (Anderson 2013; Lightfoot et al. 2013; Williams 2002). Wildlife ecologists and environmental historians now recognize African pastoralists' role in grassland maintenance by consistent application of fire as benefiting not only their herds but also wild savanna grazers (Kjekshus 1996[1976]; Homewood and Rodgers 1984; Lamprey and Waller 1990).

Given such considerations, do habitat restorers want to reset plant and animal communities toward the states in which foreign explorers encountered them? Such a goal presents its own conceptual issues and reveals how value-laden this enterprise is. Evidence from the Americas and Africa suggests that many indigenous populations crashed because of foreign diseases transmitted from colonizers along exchange systems, well *before* the first entry of European explorers into their region. This probably permitted a "rebound" in taxa formerly heavily cropped by humans, such as salmons and the wild ungulates that so impressed European explorers in western North America (Broughton 1999; Butler 2000) or in eastern and southern Africa (Kjekshus 1996[1976]; Percival and Cuming 1925). Should conservation biologists and applied zooarchaeologists aim for the "explorer encounter" state as the baseline state, or should they aim for an earlier, humanly managed landscape? If the latter, should it be the one immediately preceding disease impacts? Grayson (2011) noted that, *as the norm*, arid and semiarid regional ecosystems undergo major shifts in state within longer-term trends in climate and vegetation, probably rendering it unrealistic to aim for a very tightly defined "steady state" in such areas.

23.3.3 Conversations About Conservation: Exercises in Cross-Cultural Communication

Decisions about baselines are not simply objective, scientific ones, but rather imbued with values and preexisting views of nature, indigenous people, and even human nature. Zooarchaeologists tend to assume that defining baselines would require either paleontological or zooarchaeological data, even if historic records are available. This may be true, but they should not assume that conservation biologists, especially those tasked with the actual management of fisheries or terrestrial ecosystems, necessarily share their perspective. Lyman (1996) argued that zooarchaeologists should provide wildlife managers with rigorous standards of empirical information regarding the presence or absence of certain species in the past, to help them develop historically informed management plans. However, Lyman's own (1998) account of trying to convince Olympic National Park wildlife managers to incorporate zooarchaeological and ethnohistorical information into their mountain goat (*Oreamnos americanus*) management policies noted that this is may not be an easy road.

Reitz and Wing (2008:333) state, "Responding to management questions requires us to teach first." But resource managers often must respond quickly to policy initiatives and might have little patience for instruction in the classic sense.

Zooarchaeologists wishing to engage productively with conservation biologists must recognize several facts. If they do not, this is poor social science research and a recipe for ineffectuality. First, those responsible for conservation management decisions exist in an often-contradictory web of administrative directives and popular pressures from industry, indigenous, and environmental interest groups. Wolverton and Lyman (2012b:9) called this *political ecology*, "the social, political, economic, ecological, and any other sort of human-interest context in which conservation biology, restoration ecology, and landscape management occurs." Effective communication begins with understanding their day-to-day concerns, persisting constraints, and hot-button issues.

Second, if conservation biologists have any narratives about premodern resource use, these come from popular publications that many professionals find problematic. For example, the idea of the "tragedy of the commons" publicized by Hardin (1968), argued that any resource, but especially land, held in common is inevitably overexploited and degraded. This was uncritically assimilated into many fields, including rangeland and fisheries management and used to justify radical "reforms" of East African pastoralists' land tenure and grazing systems, traditional fishing practices in the European Atlantic, and other resource uses, without empirical research into local management systems. Research by human ecologists, anthropologists (McCabe 1990), historians (Johnson 1993) and economists (Ostrom et al. 1999) found very few cases of environmental degradation within *traditionally* managed land or fisheries, where access to "commons" is often governed by complex, culturally enforced, unwritten policies. Reitz (2004) shared her own insights on this topic with regard to fisheries.

Third, zooarchaeologists in North America, and perhaps other settler colonies, must acknowledge that conservation biologists might have images of Native peoples either as natural conservationists or unbridled extirpators. Some books in the 2000s held Native Americans responsible for massive wildlife depopulation, from extinction of Pleistocene megafauna to wiping out large mammal communities during colonial times (e.g. Kay 2002; Martin 2002). Zooarchaeologists have used documented declines or presence/absence of species in regional archaeofaunal samples, and critically assessed fundamental assumptions of such arguments (for judicious examples of these approaches, see Lyman 2010; Nagaoka 2012). Yet, the influence of one spate of popular books or another may have to be negotiated.

Finally, because their training in biological sciences stressed other areas of knowledge, conservation biologists might not believe that osteological elements, even if well preserved, can be identified to species. Zoological experts have asked me, sometimes with genuine curiosity, sometimes in a more challenging way, whether I could really tell the bones of one species from those of another. Deep breathing, tactful responses and supporting documentation are helpful.

An example of potential difficulties comes from our team's research on the occurrence of northern fur seals in central California and farther north. We contacted experts who managed the United State stocks of the species because we hoped their knowledge would help us understand aspects of *Callorhinus* ecology could have allowed the biogeographic variation we saw in the archaeofaunas. We assumed that managers would think our findings were interesting. We were cordially welcomed to use facilities and younger male collaborators were invited to visit fur seal colonies, perhaps to test of their "fiber." But then ensued a decade of challenging interactions. Informal questions were not responded to at all or dealt with on the fly without follow-up data. Critical reviews of our submitted manuscripts and grants – we suspected by these experts – referenced largely unpublished data and recommended against publication or funding. Some criticisms forced us to be more rigorous, but we did not grasp the source of the problem until submitting a manuscript that summarized our zooarchaeological, isotopic, and genetic findings (Newsome et al. 2007). One review stated the study is important because it could set a "historical benchmark" for a top predator in the north Pacific ecosystem and complimented our thorough and appropriate application of analytical techniques – yet recommended against publication. The review stated our conclusions were not justified, nor was the work of "suitable quality." The paper's biggest problem in the reveiwer's eyes appeared to be the possible harm that our research could do if "certain groups" used our data that the species was abundant along the Pacific coast of North America in pre-Columbian timessto advocate for imprudent species restoration or other actions in the present. We were urged to "search our souls" about whether we wanted this to happen. Only then did we realize that our findings were being read through the political ecology of pinniped management, in an increasingly depleted North Pacific fishery, amidst multiple and contradictory pressures from government, industry, and interest groups. We never set out to undermine managers working in such situations, but I suspect this is how our findings and questions were perceived: as potentially destabilizing "facts" from ivory tower academics ignorant of management realities.

However, this was a learning experience for everyone. Within 3 years, perhaps associated with a changing of the guard among senior conservation biologists, members of the same management unit coauthored an article with members of our research group (Pinsky et al. 2010). It discussed management implications of ancient and modern *Callorhinus* DNA and the archaeofaunal evidence for the species' past distribution. In the wake of this experience, I realized that a more culturally and politically informed approach to conservation zooarchaeology was required. When the head of a fisheries research lab on our campus invited my graduate student researching mid-latitude Pacific fish archaeofaunas to join his lab group, I strongly encouraged her to do so. She "learned the language" and became a credible actor with her graduate student peers in fisheries research. Hopefully, with this start, she will have success in discussing the fate of fishes past and present with that community. Beyond specific examples, the take-away message for aspiring applied zooarchaeologists is to understand conservation biology takes place in a sociopolitical context, and that a bit of ethnography of "one's people" can facilitate productive conversations.

Summing up this diverse chapter, stable isotope analysis and genomics offer strong proxies for past human diet, mobility, and exchange, as well as the emergence of mutualist relations in domestication, and the place of wild species in regional ecosystems – if used with care. Using archaeofaunal data in conservation biology is possible, laudable, and at the same time makes novel demands on zooarchaeologists to grasp and negotiate mutually satisfactory communication within the "political ecology" of that community's practices.

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Chapter 24
Behavioral Ecology and Zooarchaeology

Previous chapters have discussed return rates in the context of nutritional utility, and presented Lupo's (2006) analysis of Hadza transport decisions using return rates in combination with Central Place foraging theory. Both of these analytic approaches are drawn from the field of evolutionary ecology called behavioral ecology, in this case as applied to human beings. Readers may wonder why a book on zooarchaeological methodology is turning to theory. One answer is that a substantial amount of zooarchaeological research on hunter-gatherers in western North America and in the Southern Cone of South America has employed theory and method drawn from this approach, especially optimal foraging theory (OFT), part of behavioral ecological theory. Another is that, as applied to archaeofaunal analysis, this approach is a theory-driven *method* of analysis, in which the analytic units (currencies) are derived from methodologies in zoology, and the proxies for these are archaeofaunal materials.

Some archaeologists accept that behavioral ecological approaches are appropriate for working with nonhuman animals but question the usefulness of applying behavioral ecological theory to human hunter-gatherers. Recent debates over the utility of optimal foraging theory for explaining the emergence of agriculture illustrate this point (Gremillion et al. 2014a, b; Smith 2014; Zeder 2014). Others have criticized rate maximization models' focus on calories as the currency for returns, when nonhuman and human actors have been shown to sometimes expend energy to acquire foods with lower caloric returns but essential nutritional content (fats, minerals, vitamins), or even to satisfy social or cultural motivations (Hockett 2016). In terms of the latter critique, my view is that defects described may often be less with the underlying models than with the execution of studies based on them, and what these purport to show. In fact, recent publications by human ecologists and archaeologists working within a human behavioral ecological (HBE) framework have presented some of the most rigorously supported cases for people *violating* behavioral ecological predictions, where their choices and actions must explained by invoking, and seeking evidence for, other goals. Violating caloric-currency based behavioral predictions is certainly not confined to humans, as the classic study of moose patch

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choice described below shows. Such cases may underline the difference between viewing behavioral ecological models as an exploratory tool for working with masses of data and believing them to have explanatory power for all the variability in such data.

This chapter offers an overview of the history and basic premises of the field, using some simple examples and listing key publications. It then comments on central issues in applying this approach to zooarchaeological cases, specifically regarding currencies, proxies, and archaeologists' expectations about HBE models' predictions. In the process, it will note a few of the cases where an HBE approach has exposed choices not predicted by such models. In no way is this section a detailed history of behavioral ecology in general nor of its breadth of applications to humans. Rather, it gives enough detail to allow discussion of its applications in zooarchaeology. I recommend that those wishing to grasp fundamentals read the very accessible overview by Krebs, Davies and West (Krebs et al. 2012), and perhaps their edited compilation of examples from a wide range of areas of animal adaptation (Krebs and Davies 2009). Those seeking thorough reviews of archaeological and anthropological applications can consult any or all of recent publications by human ecologists and archaeologists (e.g. Bird and O'Connell 2006; Broughton and O'Connell 1999; Kennett and Winterhalder 2006). Bird and O'Connell (2012) present an especially interesting discussion of behavioral ecology in relation to other theoretical approaches in archaeology and anthropology. Finally, Bettinger (2009) offers simple, clear discussions of five behavioral ecological approaches to human foraging, with examples and exercises.

24.1 History

The field now called behavioral ecology emerged in zoology over the 1960s and 1970s, based upon an earlier generation's studies of animal *behavior*, as opposed to animal abundances, size, and other populational traits outlined in Chap. 22. Many of the founding generation of zoological behavioral studies were Europeans, including Konrad Lorenz (Austria), Nikolaas Tinbergen (Netherlands), and Karl von Frisch (Austria). They developed systematic descriptions of vertebrate and invertebrate behavior, a study then called *ethology*, positing evolutionary causes for "instinctive" patterns of behavior among various types of animals (Burkhardt 2005). Tinbergen taught at the University of Oxford for many years after the Second World War, influencing the next generation of English-speaking zoologists. Lorenz also had an impact on many anglophone zoologists, through his widely translated writings. In parallel, E. O. Wilson, an American entomologist, went from applied research early in his career to theorizing the evolutionary bases for the diversity of social-living insects and their behaviors (e.g. Wilson 1975). While Wilson's term "sociobiology" has generally been supplanted in zoology by "behavioral ecology," his influence on the next generation was substantial.

Students of these researchers, and those influenced by their writings, applied quantitative methods to the principal relationships of animal ecology, as did Wilson's student Simberloff in relation to earlier theories of biogeography. Tullock (1971) explicitly posited that microeconomic theory could be applied to understanding the choices that foraging vertebrates make. He argued that foraging behavior of the coal tit (*Periparus ater*), a small Eurasian songbird, conformed well to the "careful shopper" theorem. Other important publications of the era drew on microeconomic models. In 1976, American ecologist Charnov authored or co-authored three influential papers on interrelated aspects of optimal foraging. One dealt with the *marginal value theorem*, and presented a predictive model of how a forager would optimally exploit patchy (non-homogeneous) environments (Charnov 1976a). The second concerned prey choice (*diet breadth*), presenting a quantifiable, cost-benefit model predicting when a foraging animal would incorporate lower-ranked prey in its diet (Charnov 1976b). The third dealt with the varieties and consequences of *resource depression* in a patch that result from a predator's foraging (Charnov et al. 1976). This last is actually a more complex matter than just depleting the resource and will be discussed in detail later in this chapter. These papers all modified earlier, qualitative discussions of optimal diet by offering symbolic and graphical models that could be readily applied using quantitative observational data to assess foraging behavior (see Bettinger 2009).

Through the 1970s and 1980s, using naturalistic and experimental observations, Charnov and Orians, British researcher Krebs, and others tested predictions drawn from these models with a variety of animal species, in the process defining the field as *behavioral ecology*. While initially restricted to foraging behavior, the marginal value theorem was applied to reproduction and other areas of adaptation, as outlined by Krebs et al. (2012: Chap. 3 "Economic Decisions and the Individual"). Pulliam, a behavioral ecological theorist whose main fieldwork was with plant-avian relationships, wrote "On predicting human diet" (Pulliam 1981), in which he explored fundamental patch choice and central place theory predictions for human foragers later pursued in anthropological fieldwork. During the same period, anthropologists Winterhalder and Smith (e.g. 1981) began to explore whether the foraging decisions of human hunter-gatherers accorded with predictions drawn from these models. While they mainly used actualistic data in their research, both, and especially Winterhalder, continued their interest in HBE applications to archaeological problems (Winterhalder and Kennett 2009).

24.2 The Basics

Behavioral ecology, as part of evolutionary ecology, emphasizes the individual, both its physical body and its behavior, as the "phenotype," or unit of selection. At the same time, behavioral ecological theorists acknowledge that many animals are social in their adaptations, referring to this as their "socio-ecological" context (Douglas Bird and O'Connell 2006). Both genetically programmed and learned components of the phenotype are considered to be important constituents of adaptive behavior, the degree of these two constituents varying with the taxa, as noted insightfully by Pulliam (1981). Behavioral ecological models, and predictions drawn from them, rest on the assumption that tactics that enhance foraging success and survival are adaptive. Underlying this is another assumption: organisms that optimize energy use in all areas of life have more energy or time to spend on reproduction, and therefore achieve greater Darwinian fitness (differentially higher rates of reproduction). The family of rate maximization models applied by Charnov, Krebs, and others is often used in combination with variants of game theory, in recognition of the fact that animals do not forage, reproduce, or avoid predation in a vacuum but rather exist in complex networks of interactions among conspecifics and members of other species (Parker 2006).

24.3 Currencies

Given its origins in microeconomics, much of foraging theory quantifies the *costs* and *benefits* of an individual's foraging behavior, as a way of assessing the overall *return* to the individual of that behavior. Foraging benefits are usually framed in the *currency* of kilocalories, whereas, for reasons of practical expediency. The costs are usually calibrated by time expended, as a proxy for energy spent, a base assumption being, the greater the time expended, the more cost in calories as well. Are calories the only possible currency for use in these models? No. As Pulliam (1981:61) stated quite early on in relation to human foragers, "humans are probably more concerned about a nutritionally balanced diet than about an energy-rich one, OFT theory can predict nutrient-constrained diets but the theory becomes more complicated and the required information on the nutrient contents of wild foods is usually lacking." Pulliam made that statement in 1981, and since then progress has been made in this area. However, few HBE studies have taken up the challenge of exploring nutrient-based foraging decisions.

The key factor in a specific organism's foraging behavior may turn out not to be calories, however, by predicting the behavior expected with a calorie-optimizing model, a study may highlight the actual object of an organism's foraging behavior. In a now-classic study of moose (*Alces alces*) on Isle Royale in Lake Superior, Belovsky and Jordan (Belovsky 1978; Belovsky and Jordan 1981) found that moose spent more of their summer foraging hours feeding on bulkier and lower-quality aquatic plants, which filled their stomachs to a point that they could not consume less bulky and higher-quality terrestrial plants until hours of rumination had cleared their guts. This led to the discovery that the moose were trading off optimal caloric intake against optimal sodium consumption via the aquatic plants during the summer, in what is a sodium-poor terrestrial environment (see also Krebs et al. 2012: Fig. 3.9, as well as discussion of pica in Chap. 13). Kaplan and Hill (1992) argued that their HBE research showed Aché foragers of Paraguay sometimes opted for foods lower in caloric return but higher in returns of protein and fat.

Rather than invalidate predictions made using caloric-return OFT models, these cases illustrate evolutionary ecologist Parker's (2006:30) point that systematic OFT approaches, "are best seen *not as tests of whether animals behave optimally but as a means of testing our insight* into the moulding of an adaptation" (emphasis added). As stressed by many authors working in this mode, models are simple for a reason (Bettinger 2009:viii), as they can indicate whether processes or organisms are conforming to very specific predictions. Moreover, they can indicate when they do not, as suggested in the examples given above, prompting another cycle of research to specify the behavior's goals, as was done in the Isle Royale moose study.

The most commonly applied variations of behavioral ecological theory in archaeology and, by extension, in zooarchaeology, have been based in rate-maximizing theories of foraging behavior. This stems from the assumption that humans, like other foraging animals, must decide how to spend their time and energy in the search for food in *patchy* landscapes, where prey of variable nutritional values are not uniformly distributed in space or time, and that foraging efficiency ultimately influences their evolutionary success.

24.4 Dollars in the Lot: A Hypothetical Example of Foraging Models

This section provides explanations of common terms in optimality models, using very simple analogical examples. Here, the "currency" for foraging decisions is money, specifically, dollars.

24.4.1 Prey Choice: Ranking and Encounter Rates

Imagine that you're out for an early morning jog or stroll in your home city, and you come upon a vacant lot (which we will consider a *patch*) that has a seemingly random mixture of \$1 and \$5 bills strewn about. This is an abundant "prey" you find attractive, and no one else is around to compete with you in collecting the bills. The \$1 and \$5 bills can be considered *lower*- and *higher-ranked prey*. As an efficient forager, you will probably try to pick up as many of the higher-value bills as you can before someone else shows up. However, whether you decide to pick up all the one-dollar bills you see while searching for fives will likely depend on your estimation of how dense the \$5 bills are among the \$1 bills in the lot, this in turn being based upon how often you are finding the fives as you search (your *encounter rate*). Optimal foraging models predict that organisms choose prey types according to the benefit that each offers, ranking prey from highest to lowest value, in their selection decisions. However, their rates of encounter with such differently ranked prey also influence their prey selection.

The dollar bill example is intuitively obvious to people enculturated in a currency-based economy, but does this work for animals selecting their prey? The short answer is yes, as demonstrated by repeated experimental and naturalistic studies in a wide variety of vertebrate and invertebrate species (see Krebs et al. 2012: Chap. 3 for references). Krebs et al. (1977) experimentally manipulated food ranking and encounter rates available to five captive great tits (*Parus major*), a bird native to the British Isles. They cut mealworms into two sizes, one twice the size of the other, and offered the different-sized prey to the birds at varied rates of encounter. When the encounter rate was low for *both* larger and smaller prey, the birds took the two sizes of prey without selectivity, but as the encounter rate for the higher-ranked prey was increased, the birds began preferentially selecting the large worm segments and ignoring the small ones. This fit Charnov's (1976b) prey choice predictions, except, unlike the model's prediction, the birds did not shift to high-ranked prey in one fell swoop but rather did so gradually.

24.4.2 Costs of the Benefits: Return Rates

Returning to the lot strewn with dollar bills, at first, you may simply jam the $5 bills into your pockets as fast as you can, but as you pick up more and more bills, your pockets get so full with crumbled up bills that no more will fit into them. You realize that it's more efficient to flatten out the bills and more carefully roll them. This takes a little time, and you worry about someone else coming by before you can arrange your stash of bills efficiently, but you figure the time spent is worth the risk because it significantly increases your capacity to pack the bills away. In behavioral ecology, the time (and energy) you spent looking for those higher-value bills is called *search time*, while the time (and energy) you spend flattening and folding the bills would be called *handling time*.

Now imagine a nightmare scenario in which the $5 bills are each encased in those thick plastic covers that consumers encounter enclosing high-value items in stores. The covers are so stiff and bulky that it's hard to put more than a few bills in your pockets. You weren't carrying your reusable shopping bag on your run, so you decide it's best to get each one out of the plastic as you encounter them. But you also left your Swiss Army knife at home because you were going out for an unencumbered run/stroll. Working the bills out of the plastic adds considerably to your $5 handling time, and after struggling with the covers of couple of bills with your nails and teeth, you begin to wonder if the time, energy, and risk to dentition you're expending on retrieving the $5 bills would be better spent simply picking up as many loose $1 bills as you can over the same interval. At this point, you are assessing your *return rate*, that is, the benefit of the prey type, once you have factored in your costs of obtaining it, in this case, handling time. If an animal prey puts up a big fight with a predator, or a plant prey such as walnut with a shell that must be cracked open before the nutmeat can be eaten, these represent increased handling costs.

Return rates are thus the *net income*, rather than the *gross value*, of a resource, once the average costs of locating and handling the resource are deducted from the resource's absolute value. Return rates for many plant and animal prey have been documented, including for human hunter-gatherers, and are essential for assessing decisions about prey or patch choice (Douglas W. Bird and O'Connell Bird and O'Connell 2012).

24.4.3 Resource Depression and Patch Choice

Going back to the original vacant lot example, where 5 and 1 bills had the same handling times, other costs can be considered. After the initial adrenaline rush of picking up free money, you may be getting a bit tired and hungry, but you decide it's worth deferring a meal to getting all those fives and ones. Searching for prey thus costs the forager energy as well as time, and handling can sometimes be costly. Foraging animals that eat their prey immediately can refuel themselves as they go, replenishing at least some of their expenditures. Birds, mammals, and socialinsects that collect food and them move it to a safer location to consume it (Chap. 12) may have to leave the patch to do so.

If this lot were the only one in town strewn with money, and you continued to be able to collect on your own, you'd probably collect the high-value bills first, then circle back to collect the low-value ones. But imagine that, as you forage, you come upon a five with a note taped to it, saying that one block east on the same street, there is *another* vacant lot with an identical distribution of fives and ones. You need to assess whether you have collected enough of the fives from the first patch to justify your abandoning it, with its remaining ones and perhaps a few fives, and head over to this second patch, where you have reason to believe you can collect quite a few more fives.

This example illustrates the basic relationships behind Charnov's (1976a) marginal value theorem of patch choice. A predator in a patch, by virtue of its foraging, lowers the encounter rate for the higher-ranking prey it selects. This is known as *resource depression*, which actually can result from several causes, in this case, being *exploitation depression* (Charnov et al. 1976), see *Varieties of Resource Depression* below. The marginal value theorem stipulates that, at a certain point, the forager will abandon a depleted patch to forage in a new one likely to have a higher density of profitable prey, regardless of the causes of the resource depression. The point at which the switch from one patch to another occurs is called the *giving up threshold* or *time* (GUT) in the literature (Fig. 24.1).

24.4.4 Trade-Offs and Opportunity Costs

Which prey items to choose and which to ignore, or when to move to another patch, are examples of *trade-offs* between costs and benefits by foragers. Returning to the vacant lot analogy, when you focus on picking up fives, you are not picking up ones, and while you are in the first patch, you can't be reaping the benefits of the second.

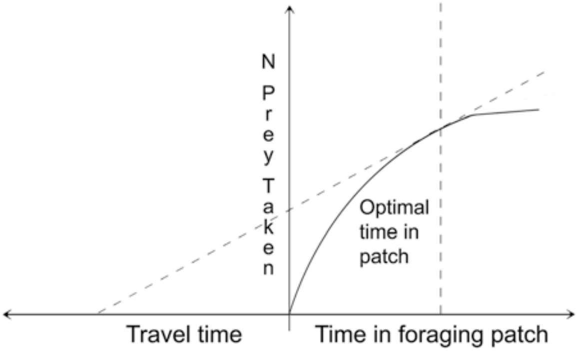

Fig. 24.1 Diagram showing the relations described in the text example of Charnov's (1976a) marginal value theorem. Travel time and time spent foraging in a patch are predicted to, and have been established experimentally to, have a complementary relationship, with shorter travel times leading to more time spent (and more prey taken) by a forager in a patch. This is an especially important relationship for central place foragers. As a forager searches for, encounters, and handles prey in the patch, their encounter rate falls off over time (curved line). The optimal solution (dashed vertical line) for the forager to choose to leave the patch lies where a tangent drawn from the travel time starting point intercepts the curve of cumulative prey taken in the patch. Beyond this point in the foraging bout in the patch, the forager is predicted to experience diminishing returns and should move to another patch (the giving-up-time). The same theorem has been demonstrated to apply to other aspects of foraging choices as well as to mating behaviors in a range of animals (Krebs et al. 2012: Chap. 3) (Redrawn by the author from Open Access Wikipedia entry "Marginal Value Theorem," https://en.wikipedia.org/wiki/Marginal_value_theorem.)

When you leave the first patch for the second before you harvest all the bills, you risk losing them for good. Behavioral ecologists use a phrase drawn from microeconomics, *opportunity cost*, to describe the loss of an alternative benefit when one chooses another one. Efficient foraging minimizes such losses, by choosing prey and patches that provide the greater return overall.

Few animals seldom have the luxury of foraging in landscapes without any risks to their wellbeing and may have to modify their optimal foraging behaviors to avoid predation, incurring opportunity costs and sometimes, added energetic costs. Young monkeys have to learn when the fruit hanging at the end of an increasingly thin limb is not worth the risk of breaking the bough and plunging toward the ground. Deer may avoid a food-rich patch if they scent a puma's urine scent-mark. Leopards often transport prey their own body size to trees, caves, or cliffs, to avoid being ambushed by other predators (Chap. 12), and so on. In doing so, leopards trade-off the best energetic solution for handling the prey – consuming it at the kill locale – against the time and energy needed to protect themselves from attack and their prey from appropriation.

24.4.5 Central Place Foraging

Back in Lot #2, you are still without competitors but your pockets and even your tucked-in t-shirt are overflowing with fives. Let's say your studio apartment is 8 blocks away. You consider whether you could hustle home unobtrusively, dump the money on your bed, and make another run back to Lot #2 for some more currency. You are thinking through some of relevant aspects of central place models (CPM) of foraging. Like nesting birds or baboons sleeping in trees to avoid predators, human hunter-gatherers forage out from a central place and then return to it; people following other economic pursuits also pivot their activities around home bases. While the central place's location may vary over time, such a spatial pattern of foraging imposes an additional constraint upon the forager, as travel time from and to the central place is a built-in component of the adaptation. So, another variable is introduced here: travel time (Fig. 24.1). Your apartment is only 8 blocks away, a 16-block round trip, but what if your apartment were 16 blocks away, a 32-block round trip? Might your assessment of the tradeoffs involved be different?

This demand is intensified in taxa with adaptations that involve carrying food or other useful items (twigs for a nest, toolstone) back to the central place, as do birds rearing young, terrestrial carnivores provisioning offspring or kin, and human foragers. The forager that collects over and above their own energy needs to provision their young or other kin face intensified energetic demands. They must search for and capture prey surplus to their own needs and then carry these some distance, all within a survivable energy budget, as illustrated by Krebs et al. (2012: 53–59) with examples of starlings and bees. Animals that have such adaptations may front-load energy stores in their bodies to cover the demands of seasonal reproduction. Other species, like you with your dollars, "squirrel away" the gathered surplus for leaner seasons.

In such systems, the round-trip's cost is augmented by the costs of transporting useful materials on the inbound trip, which you almost but not entirely would avoid with your inbound burden of paper currency. Such costs and benefits must be factored into those already outlined in terms of return rates. Harking back to Chap. 19's discussion of butchery, discard, and transport decisions, especially Lupo's CPM-based analysis of the Hadza data, one can grasp that a forager may choose to shed the less useful parts of a resource to facilitate transfer of more useful parts at lower costs. This is especially possible for tool-using humans, who can pre-process various materials, from lithic raw materials to plants and animals.

Metcalfe and Barlow (1992) developed a theoretical model of the trade-offs involved in field processing. This takes into account the average utility of a resource (energy, etc.), the proportion of that resource's "package" with that utility prior to its field processing, the size of an optimal carrying load of the resource, the time required to field process the "package" to strip away less useful components for such an optimal-weight load, and the transport time between the locale of procurement and the central place. They also noted that "field processing" some packages may entail several temporally discrete stages, and that a processor may choose to transport a load before all stages are accomplished, if this is the optimal trade-off, given other factors. Bettinger et al. (1997) applied such CPM to acorns and mussels, using return rates and caloric costs of transport to calculate the distances past which inedible parts of these taxa should not be transported to a central place from their points of acquisition. As did Metcalfe and Barlow, they noted that such decisions could involve additional trade-offs. The more time that is spent on field processing to lighten the load, the less time is available for gathering the resource, a situation further constrained when the forager wishes to get home by sundown.

24.5 Varieties of Resource Depression

The foundational writings on patch choice and resource depression recognized that several types of processes and outcomes might make prey less available to predators (Charnov et al. 1976). *Exploitation depression* is the sort of resource depression most of us may imagine initially, in which the harvesting of prey by a predator significantly reduces the number of individuals of that taxon in the patch, thereby lowering encounter rates, as was true in the hypothetical case of collecting most of the $5 bills.

Charnov et al. (1976) outline other means by which the availability of prey may be depressed. These include *behavioral depression*, in which changes in prey behavior render them more difficult to encounter or capture, including changes in alertness, flocking or schooling behavior, and reductions in intraspecific display activity when predators forage. Prey may remove themselves from a vulnerable microhabitat to less vulnerable places, producing *microhabitat depression* (Lyman 2003). Charnov et al. point out that prey numbers may not actually be depressed numerically in either of the latter cases, as opposed to the reduction in prey numbers typical of exploitation. Charnov et al. also note that, in the latter cases, predator search times increase without appreciable diminution in the numbers of prey, potentially shifting the ranking of the prey species, as their return rates change. They note that prey reproductive rates as well as their feeding behaviors are key to understanding the nature and demographic effects of resource depression. Species that must forage for long episodes in a specific microhabitat to obtain enough food (continuous feeders) may be more vulnerable to the knock-on effects of predator avoidance on their fitness than are taxa that can "grab and run" (discontinuous feeders), consuming or digesting food from one microhabitat in another, less vulnerable one. Charnov et al. note that predators may cope with microhabitat depression by altering their prey search tactics or even by "collaborating" with other predators at intra- or interspecific levels.

In zooarchaeological research, both Butler (2000) Lyman (2003) have argued that behavioral or microhabitat depression, as well as exploitation depression ("driving a species extinction") must be considered.

24.6 Beyond Rate Maximization: State Modeling Approaches

Most archaeologists have restricted themselves to "static" patch and prey choice models based upon caloric rate maximization. However, soon after the initial round of rate maximization models were developed, zoologists developed and explored more complex approaches assessing and predicting foraging and reproductive behavior in the context of overall fitness (Houston et al. 1988; Houston and McNamara 1985; Clark and Mangel 1984). These dynamic state variable models

(DSVM) have been used in foraging behavior research in both academic and applied (e.g. fisheries) research for well over 30 years. As applied to foraging, DSVM models take into account the *prior foraging history and energetic state of the forager* at the beginning of a foraging bout. DSVM analyses have been applied to reproductive as well as foraging behavior (e.g. Luttbeg et al. 2000), and in such cases, the state and currency variables are different. As described by Clark and Mangel (2000:3), DSVM uses iterative computer modeling to, "link the physiological states of organisms with the environment via a natural measure of Darwinian fitness."

DSVM requires formal definitions of the state variables of interest, constraints and trade-offs, the time interval the model will cover, what decisions the organism needs to make, and how the results of those decisions will affect the organism's fitness. In a diet choice model, for example, the characterization of physiological state might be a forager's caloric reserves, and the model might be used to predict the optimal pathway(s) toward the forager's banking enough nutrients to survive and reproduce, under conditions that vary according to expectations about caloric costs of foraging, caloric returns of multiple prey taxa, the likelihood of success in obtaining a given prey taxon, the risks of forager mortality while foraging in specific patches, all within a stochastically varying environment (Clark and Mangel 1984, 2000). These authors stress that the model permits addition of any relevant variables that could be considered simultaneously with calories, so that those of us interested in nutritional ecology (e.g. Hockett and Haws 2003; Moss 2016) might include fats, EFA, or even more closely specified nutrients.

The optimal solution indicates patch or prey choices through which a forager is predicted to obtain the best caloric returns while avoiding death from either predation or starvation, thus being both alive and in the best position to reproduce. Once the model has shown such optimal patch choice pathways, multiple Monte Carlo simulations are run, often in hundreds of iterations, to predict the outcomes of a forager following those optimal choices under variable environmental conditions. Since DSVM allows for a stochastic environment, the model allows that a forager may or may not be successful in capturing prey, even after making "correct" choices. The aggregate pattern of outcomes from the forward iterations of the model can provide predictions that are testable with the "real world" systems the model represents. Clark and Mangel's (2000) introduction is a clear exposition of the method, its advantages, and prior uses. In her open access dissertation Boone (2012:279–315 plus appendices) provides an accessible description of the process, using patch choice as the focus. The open access software R for UNIX, Windows, or Mac offers a DSVM modeling program (The R Foundation 2017).

Beyond studies of forager and pastoralist reproductive ecology (Anderies 1996; Mace 1996), anthropological applications of DSVM have been limited. Mace (1993) used DSVM to assess conditions under which Gabbra pastoralists with differing livestock wealth would pursue different sheep flock management strategies to guarantee long-term household survival in the face of drought in arid East Africa. Specifically, the model assessed long-term outcomes of offtake maximization (allowing maximum breeding rate) versus growth-slowing tactics. Given that ewes that do not breed during prolonged drought displayed relatively lower mortality than did breeding females, the model explored at what number of ewes does limiting ewes' chances to breed emerge as the prudent solution. The model's outcomes predicted that growth-slowing tactics would be the optimal long-term solution for households with low flock numbers in a stochastically variable environment. Mace observed the predicted tactical divergences between poor versus wealthy Gabbra households in her fieldwork (see also Mace 1989).

Under the mentorship of Mangel, one of the developers of DSVM, zooarchaeologist Boone (2012) developed a model for fish exploitation in Monterey Bay, California. She chose to investigate patch choice, as reflected by animal taxa typical of the area, including various marine habitats and a generalized terrestrial patch including such taxa as deer. As would a rate-maximization model, the model assigned an energetic benefit to each taxon, but additionally estimated a risk and energetic cost of failure to capture each prey species that would count against the forager's energetic state in the next bout, plus estimates of risk of mortality to the forager presented by different patches where prey were located, and it finally set variable patch conditions. The results of the DSVM predicted that foragers would achieve optimal fitness by exploiting predictable, easily acquired resources, which offered the highest reliability of prey capture under variable conditions, even when these offered somewhat *lower* returns than did those offering the highest caloric return per capture, as would be favored under a rate-maximization model. Significantly, Boone found that the model's predicted "solution" regarding patches and taxa generally predicted the patch choices reflected in 13 trans-Holocene archaeoichthyofaunas from Monterey Bay. The only exceptions were samples from the time span immediately after the Medieval Climatic Anomaly, when deeper-water prey such as sardines, offering both heightened risks of mortality to the forager but high levels of fats and EFA, emerge as a major prey item. Over the same period, safer tidepool species also rise from steady but low proportions to a statistically significantly higher share of the samples. Together, Boone argued that these findings suggest diversified foraging investments and intensified risk-taking in obtaining marine resources as terrestrial ecosystems recalibrated following severe drought. As with the Mace (1996) study, the take-home message of Boone's work was that ensuring reliable, steady inputs over time by choosing low-risk patches and prey, rather than tactics that maximize offtake but have higher risks of failure, helps to optimize fitness in most – but not all – cases.

Behavioral ecologists Jones et al. (2013) reached similar conclusions regarding a preference for variance reduction using data from present-day Martu foragers in Australia. Using a different modeling approach (a two-component finite mixture model), which integrated, "information on the nonlinear preferences for different energetic returns with the distributional information about the likelihood of differing returns" (Jones et al. 2013:6) used data from Martu men's hill kangaroo hunting and women's sand monitor lizard hunting to explore whether rate maximization or variance reduction best accommodated the actualistic returns data. Over the long-term, reduction of variance in animal-based caloric income, rather than rate maximization, is favored in the model (Fig. 24.2).

To sum up, these more complex approaches, all of which incorporate a time dimension, yield different results than do traditional, rate-maximization models and

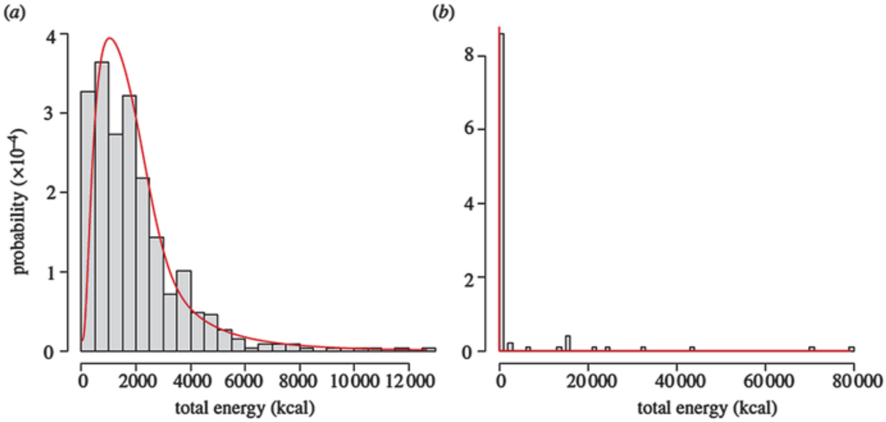

Fig. 24.2 (**a**) Empirical (shaded bars) and best-fit probability density (red lines) for Martu sand monitor foraging returns and (**b**) empirical and best-fit probability density for Martu hill kangaroo foraging returns. This visually condenses the results of Jones et al.'s (2013) two-component finite mixture model analysis, which integrated data on nonlinear preferences for different energetic returns with distributional information on the likelihoods of the differing returns. It shows that sand monitor kilocal returns, while much lower than those for hill kangaroo, have much higher likelihoods of actual return (greater predictability) in Martu animal prey intake. (From Jones et al. (2013:6, Fig. 3), used with permission of the authors and of the Royal Society of London)

must be seriously considered as offering a more realistic model for archaeofaunal patterning. Lupo (2007) stressed that methodological progress in zooarchaeology depends on consideration of the forager's condition, including their social status, energetic reserves, and reproductive capacity, as well as the specific context of their subsistence decisions, and such models do this. The examples cited here demonstrate that more complex modeling is possible with tools already widely used in other contexts, and, more importantly, yield solutions that may better accommodate archaeologically and actualistically derived data.

24.7 Proxies Yet Again

Whatever approach to foraging choices is used, proxies are critical for zooarchaeologists to consider because we cannot proceed without them. In the currency-based approach that characterizes all foraging analysis in behavioral ecology, archaeologists must consider two questions about their proxies. The first is the nature of the proxy itself: since neither the humans nor the animals under study can be directly observed, what proxies can replace the classic OFT proxies of success: search and handling time in relation to caloric return? The second is one's background assumptions about the cause of patterning in the chosen proxy. These are considered in turn here.

24.7.1 Nature of the Proxy

Recall that, in the behavioral ecology of living species, prey rank normally has been calibrated by *caloric return*, while search and handling energy expenditures are calibrated by *time spent, rather than by calories*. Furthermore, optimal caloric return itself stands as a proxy for fitness, which nearly always is assumed rather than demonstrated (Bird and O'Connell 2012). Thus, in research on contemporary animals, a proxy for energy – time – is used for foraging costs, and the energy benefit is a proxy for fitness. For archaeologists applying rate-maximizing models, *prey size* was originally substituted for caloric income, thus substituting a proxy for a proxy (Boone 2012:195). At first, prey were ranked simply according to individual body size, but later discussions of returns from some cases of technologically aided mass capture of smaller prey have modified the ranking of some smaller prey (see Ugan 2005b for a review). A small-bodied taxon may move higher in prey rankings if their return rates in mass capture and processing are high, as they would be with net-caught herring (Moss 2016). Prey ranking by return rate may have to factor in costs of technological inputs such as trap or net production and maintenance (Bettinger et al. 2006; Ugan et al. 2003).

Zooarchaeologists have also used caloric and other nutritional values instead of body size. Many such values are available from published nutritional tables available online, as in the U.S. Department of Agriculture's National Nutrient Database for Standard Reference which include listings of traditional American Indian and Native Alaskan foods (https://ndb.nal.usda.gov/ndb/). Other governmental organizations have compiled comparable tables for other regions of the world that include wild animal foods (e.g. Dignan et al. 2004). Some zooarchaeologists have commissioned nutritional analyses of certain species, to explore nutritional values of foods not currently listed on such public sources, as did Boone (2012) for prickleback fishes (family Stichaeidae), which are not commercially exploited today. Nutrition sources do not report handling times, so researchers still must engage in actualistic some data collection to get to return rates (e.g. Thomas 2014).

In part due to low NISP for any given species, zooarchaeologists have lumped taxa that inhabit the same patch, such as freshwater or marine fishes (Butler 2001) or inland versus coastal patches (Nagaoka 2001) in their analyses. Using a method first applied regionally by Broughton (2002), Boone's (2012) study divided marine fishes into patches according both to habitat and to method of capture (e.g. estuarine or boat mass capture), based upon ethnographic accounts of prey acquisition.

24.7.2 Assumptions About Causes of the Proxy

The second aspect of the use of proxies, what one believes *caused* the observed patterning in remains of a species or group of taxa, must also be considered. Since most zooarchaeological research in this area has involved resource depression, the issue can be explored using some examples from that literature. One commonly used indicator of resource depression is a change in the abundance ratios of higher-ranked taxa versus lower-ranked taxa:

$$\frac{\sum \text{NISP high} - \text{ranked taxa}}{\sum \text{NISP high} - \text{ranked taxa} + \sum \text{NISP low} - \text{ranked taxa}}$$

In North America, a simplified "Artiodactyl Index," involving wild ruminant artiodactyls (e.g. deer, elk, antelope) and wild lagomorphs (rabbits and jackrabbits) has been very widely used, starting with the influential work of Bayham (1982). The index is simple to calculate, and, in many cases, it appears that diminution in the numbers of larger prey is occurring, especially with evidence for increased human population and/or sedentism. Many cases of a progressive diminution of the ratio of high-ranked to low-ranked ones are archaeologically documented, as in the Butler and Nagaoka studies cited earlier, and that of Broughton (2002). Whether the causal mechanism is simple, individually driven over-hunting of prey through time, or whether changes in social organization and political economy may drive such resource depression, is a matter of some debate (Speth and Scott 1989).

Some researchers have cautioned that one must systematically consider and eliminate causes other than exploitation depression for shifts in a prey species index or evidence for selection of lower-ranked taxa. Schmitt and Lupo (1995) urged zooarchaeologists using Great Basin rockshelter samples to consider agents of bone accumulation and site formation other than humans, which can sometimes be teased out with analysis of taphonomic modifications, before analyzing faunal samples. They point out that the accumulations of raptors and wild canids in such deposits can, if not factored out, skew indices of high-ranked (usually large) to low-ranked (usually small) prey. Ugan (2005a) made the case that taphonomic factors, plus dendrochronologically documented climatic variability, rather than simple overexploitation, were responsible for changes over time in two Fremont archaeofaunas from the Parowan Valley of Utah. Both Lupo and Schmitt (2005), using actualistic African data, and Codding et al. (2010), using contemporary Australian data, have commented on the variety of forager decisions that can change abundance indices without any hint of resource depression.

Lyman (1989), Stiner et al. (2000), and Broughton (2002) have all stressed that zooarchaeologists wishing to study resource depression are best served by understanding the behavior and reproductive dynamics of target species. Signs of resource depression in different taxa may manifest differently. In species of indeterminate growth, such as many reptiles and fishes, reduction in modal size of captured prey has been accepted as reflecting exploitation depression (Klein and Cruz-Uribe 1983; Broughton 1997; Stiner et al. 2000). In species with determinate growth, a shift in age classes may suggest the same, with younger animals chosen, but Broughton (2002) cautions that, in species that defend their young, cases of intensified focus on young of the year may be accompanied by an increase in adults who sought to repel human predators. Whitaker (2009, 2010), in reviewing the zooarchaeological literature on resource depression, has argued that zooarchaeologists have generally assumed that declines in species abundances over time in their assemblages reflect exploitation depression. He contends that that a more rigorous approach, which takes into account the biology of the species, especially its reproductive ecology, can separate cases of behavioral depression from those of true exploitation depression.

24.8 Behavioral Ecology and Social Zooarchaeology

It is my point of view that the most interesting and powerful aspect of HBE's application in archaeology lies its ability to expose cases in which people do *not* behave like "optimal foragers" but instead choose or are forced to collect or transport food in some other way. Bird and O'Connell (2012:41) state:

> The real utility of such models lies in the specific way that their predictions are at risk of failure relative to observed behavior and its material correlates. Such failures then point towards new questions. If agents do not behave as modeled, it's not their fault (i.e. it doesn't necessarily mean their behavior is maladaptive), nor is it the fault of the theory, for that matter. Rather it suggests the existence of one or more problems with the specific hypotheses at risk in the analysis.

In other words, by controlling predictions about an universal human behavior, food-getting, one can better specify the "mismatches" in which goals other than caloric or even other nutritional gain may be at work.

A few examples illustrate this point. Hildebrandt et al. (2009) used shellfish return rates and Central Place Model (CPM)-based transport predictions developed by Bettinger et al. (1997) to evaluate the occurrence of shells of marine clams in Laguna de Santa Rosa archaeological sites, some 25 km inland from the Sonoma County, California coast. The substantial quantities of clamshell recovered from these the sites were at variance with transport predictions based on CPM. The authors argued that this reflects seasonal acquisition and transport of fresh clams to support feasting, during a phase of increased elaboration of cultural practices and internal societal differentiation in the region. Hildebrandt et al. (2009) interpreted the high transport costs as ostentatious display in the broader context of elaborated feasting practices.

Whitaker and Byrd (2014) argued that marked increases in very small-bodied mollusk species, *Cerithidea* in south San Francisco Bay archaeofaunas and *Donax* in southern California coastal ones, reflect not the over-exploitation of higher-ranked species but rather constraints on local populations of territorial circumscription in densely populated areas. They posit that prey choices reflected more localized foraging opportunities in such political circumstances, which nonfaunal evidence supports. They argued that, "shifts in social interaction and demography are as important or more important in driving patterns of shellfish exploitation than biological and ecological processes" (Whitaker and Byrd 2014:150).

Thomas (2014) noted that a shift toward lower-return maize cultivation accompanied by reduced exploitation of higher-return shellfish on St. Catherine's Island coincides with the appearance of late Mississippian iconography. He argued that this subsistence change toward less-than-optimal returns reflects not the exhaustion of shellfish on the island but rather incorporation of its inhabitants into a socially differentiated society and political economy, in which maize cultivation, for all its inefficiencies, was driven by social factors. Other such cases are cited in Bird and O'Connell (2012) and in Bettinger et al. (2009).

24.9 The Importance of Actualistic Research

Bird and O'Connell (2012) stress that actualistic research is central to applications of behavioral ecology in archaeology. The present day is the only context to develop the "middle range" theory that defines nutritional values, handling time estimates, return rates, transport costs, and other variables employed in the generation of hypotheses. Moreover, it is the only place to gain a realistic perspective on how well and in what ways foragers in the real world conform to predictions of the models. Bird and O'Connell (2012) cite a number of studies that demonstrate living forager behavior coinciding with predictions (e.g. Bird and Bliege Bird 1997), but also quite a few that show foragers diverging from them. These include Bird et al.'s (2013) exploration of the social reasons why Martu hunters of the Australian Western Desert avoid killing and eating ubiquitous feral camels, despite living with them for about a century. Moreover, actualistic research with hunter-gatherers has provided insights on commonly used abundance indices and other methodological assumptions. Using observations from present-day Bofi foragers, Schmitt and Lupo (2008) systematically explored whether better hunters' food refuse or artifacts reflect their differentially greater competence.

At the level of site formation, Bird and Bliege Bird (2000) showed that that molluscan fauna at residential campsites do not simply reflect adult foraging and transport choices but rather combine these with products of children's foraging, which is dictated by children's differing body strength and mobility. What is optimal for a foraging child is not so for an adult, and such actualistic observations indicate that zooarchaeologists should be alert to the possibility that several tiers of foraging efficiencies may be reflected in archaeological sites (Gifford-Gonzalez et al. 2006:48).

Behavioral ecologists working with modern human foragers in a variety of settings continue to debate the reasons why, on a global scale, tropical to temperate latitude male hunters seldom pursue foraging strategies that would ensure their families the most reliable inputs of animal protein. Possible reasons and the tradeoffs for higher risk-of-failure male hunting are outlined by Bird and O'Connell (2012) as well as Jones et al. (2013), and these should be considered by zooarchaeologists interested in "efficiencies."

24.10 What Kinds of Models Make Trustworthy Predictions?

On the one hand, this chapter has made the case that formulating clear, testable statements drawn from rate-maximization models can reveal cases where people's choices and actions deviate from predictions based on these models and need to be explained by invoking other goals than maximizing energy capture. On the other hand, this chapter has also made a case for moving to more dynamic and complex behavioral ecological models, suggesting that these sometimes produce different solutions than do those based upon static rate maximization. Doesn't the second statement contradict, or at least jeopardize, the first? Can we have it both ways? For the time being, I think it's possible to do so, because the definitive work needed to assess whether the second set of models always does the job better than the first has not yet been done. Until the static versus dynamic models are systematically assessed using the same datasets and multiple cases, it's difficult to know whether they always produce different outcomes – as suggested by two studies using different dynamic modeling approaches cited here (Boone 2012; Jones et al. 2013). Moreover, it's unclear whether, in actualistic cases, the predicted optimal solutions of either consistently converge on actual, documented choices. This exercise is the same as deciding whether one piece of lab equipment produces better results than another when doing the same job. It needs to be done. In the meantime, it's my point of view the admittedly crude predictions drawn from rate maximization studies cited above are provocative and should not be dismissed, but they are not definitive.

24.11 Behavioral Ecological Predictions are Not Uniformitarian Principles

The foregoing sections, outlining as they do the fact that researchers have regularly encountered cases in which nonhuman animals and human foragers violate the predictions from rate-maximization models, suggest one way that behavioral ecological models *cannot* be used. Archaeologists rely upon uniformitarian processes because of their value in developing trustworthy inferences based upon relational analogies with which to develop narratives or scenarios accounting for a certain configuration of evidence (Chap. 3).

Predictions derived from behavioral ecology may, with the intelligent use of proxies – and screened through taphonomic analysis – elucidate human choices that produced certain patterns of archaeological evidence, or point the investigator elsewhere than rate maximizing behaviors. The models and predictions drawn from them are best seen as *tools for inquiry*. In and of themselves, they do not provide *explanations* of archaeological cases without lapsing into a kind of circular reasoning identified by Hockett (2016). The causal relationships stipulated by the theory are neither necessary and sufficient conditions for all foraging choices, nor does the "tower of proxies" upon which mainstream rate maximization exercises rest inspire absolute confidence, as noted by those opting for more complex modeling (Boone 2012; Jones et al. 2013; Lupo 2007). Reliance on behavioral ecology to explain rather than to explore, without rigorous, evidence-based support from outside the modeled behavior, may drift into what Zeder (2014) has in another context called "faith-based science."

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Chapter 25
Social Relations Through Zooarchaeology

Among foragers, farmers, pastoralists, and members of complex societies, animals and their products are sources of tension and conflict as well as means of mediating these. Animal foods in particular are nearly always the subject of economic manipulation, with access to them often governed by age, gender, or social status. Among food producers, living animals are often highly desired as possessions. For zooarchaeologists, the question is not *whether* animals are woven tightly into human social relations but *how to investigate* this with archaeofaunal evidence. This chapter reviews a variety of approaches to these issues. It shows that many zooarchaeological methods summarized in prior chapters can address socially focused questions. It begins with discussing traditional approaches to "social archaeology," and how the studies cited in this chapter differ from these. It then proposes a set of methodological and conceptual tools for working with archaeofaunas with a socially focused perspective.

This chapter concentrates almost exclusively on the *social* aspects of zooarchaeology, rather than upon *cultural* aspects of animals as symbols or their place in ideological systems; these have been excellently covered by Russell's *Social Zooarchaeology* (2012). In a largely methodological book, I am opting to work with those aspects of human social life that might be recovered from contexts lacking ethnographic or documentary linkages. In other words, I focus on situations where I believe it may be possible to investigate social choices and practices relating to animals, but where, if such sources for analogy are lacking, the places of animals and their products in symbolic systems cannot be explored with the same confidence. In this, I take inspiration from Ann Stahl's (2002) essay on alternatives to logocentric (meaning-centered) approaches in archaeological analysis (Gifford-Gonzalez 2013).

Archaeologists have been more inclined to explore social relations in "complex societies," large-scale, occupationally diverse and socially stratified polities (McGuire 1983). This stems at least in part from the relative ease with which such relations can be inferred from the aggregate evidence of settlement patterns, architecture, artifacts and features, burials, art and even documents produced by such

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societies. Archaeological studies that focus on settlement hierarchies in landscapes, internal organization of cities, monuments, and treatment of the dead in such societies have revealed unique social histories and relations (e.g. Renfrew 1986; Pauketat 2004; Monroe and Ogundiran 2012; Yuan and Flad 2005; Cowgill 2015). The concatenation of so many multiple lines of evidence certainly permits inferences about patterns of social behavior and relationships when compared with the much sparser materials produced by most small-scale societies.

However, the tendency for social archaeology to be the archaeology of complex societies may also be rooted in implicitly evolutionist thinking, never completely expunged from archaeology, that sees foraging peoples as egalitarian, farming communities as occasionally producing ranked societies or chiefdoms, and so forth. This may be accompanied by the unarticulated notion that "nothing interesting" happens in the "simpler" social formations. Evolutionist assumptions, implicit or explicit, have been challenged on multiple grounds, including by researchers working with the archaeological record of "complex hunter-gatherers" (Price and Brown 1985; Hayden 2009) and by those who see the lack of fit between evolutionism's limited range of developmental phases and the diversity of social forms in the real world (Stahl 1999).

Ethnographic cases demonstrate that assuming mobile hunter-gatherers are or were "egalitarian" is problematic. Among foragers, age and gender determine social status, rights, responsibilities, and control over specific tools and resources. Such societies do place a strong ideological emphasis on equality, but it is equality of men among men and women among women, with children forming a third category, having different rights and responsibilities from adults. With regard to animals and their products, men and women play different roles in acquiring, distributing, and consuming them (Fig. 25.1). Many pastoralists espouse an egalitarian ideology, but careful, comparative studies of wealth transmission indicate that this is often a "party line" rather than an actuality (e.g. Borgerhoff Mulder et al. 2010). For archaeologists, the question once again is not whether inequalities existed among foragers and other ostensibly "egalitarian" societies, but how to discern such differences with the archaeological materials that we have. Since diet is one area of life where social distinctions based on age and gender are habitually enacted, zooarchaeology offers a potential tool for investigating social relations (Russell 2012; Twiss 2008).

25.1 Archaeofaunal Remains as Evidence for Social Relations

Until recently, theoretical tools for investigating social relations in everyday life, from which the preponderance of archaeofaunas derive, have been lacking in Anglo-American archaeology. Traditional processual approaches, while strong on methodology, displayed a polarity between technology-wielding individuals and "systems," with little attention to the daily life of corporate groups and communities as the

Fig. 25.1 A socially situated meal: mutton and cornmeal porridge feast in author's camp at Ileret, Lake Turkana, Kenya, after author-documented slaughter of sheep during her ethnoarchaeological research. Meat selection and seating by gender and age. Author (behind camera) ate offered roast meat (men's food) and sat with women. L-R cook and informant Loriano Kesia, field assistant Jack Kilonzo, (back to camera) Senior Chief Asurra, unknown man, field assistant Andrew Kilonzo, Administrative Chief Randille, son of Chief Assura, Chief Randille's daughter Kolum, his mother Abarrio, his wives Sani and Nalitchu, and other children. (Photo by author 28 February, 1974)

contexts in which individual decisions are taken and archaeological deposits are produced. This bias may reflect unarticulated Anglo-American assumptions about individualism cast onto archaeological research questions. Moreover, as Hodder (1991) observed, though postprocessual theory emphasized "agency" and advocated the study of individuals and interest groups, it did not articulate practical means for doing so archaeologically. Even Anglo-American studies of gender, a quintessentially socially constructed category, may sometimes be circumscribed by a lack of attention to the broader social medium of human identity, decisions, and actions (Gifford-Gonzalez 1998).

The first step, as advocated long ago by Conkey and Spector (1984), may simply involve reframing what is already known from a different perspective. For example, Wheat's (1972) narrative of a bison hunt and butchery from evidence at the Olsen-Chubbuck site is a story about predation and processing. It is also a story about socially coordinated work by persons of different ages and genders. Wheat recognized this and recruited – perhaps uncritically, by contemporary standards – Plains Indian ethnographic analogues to tell that part of the story. Even without such formal ethnographic analogies, we intuitively grasp that the disassembly and systematic spatial segregation of body segments of animals as large as bison, on a scale such as that at the Olsen-Chubbuck, Horner or Glenrock sites, implies the differentiated and coordinated tasks of a social group, a largescale, multi-person *chaîne opératoire*. I recently reframed some of my own ethnoarchaeological research and archaeofaunal analysis from East Africa (Gifford 1977; Gifford et al. 1980), using a perspective on refuse disposal activities as socially embedded acts (Gifford-Gonzalez 2014), as will be discussed later in this chapter. In fact, most of the topics covered by this book – hunting tactics and selectivity, butchery and distribution of carcass parts, food processing and preservation, age-specific culling, long-distance human migration and exchange – are either accomplished by socially coordinated actors in households or larger social groups or by individuals working toward social goals. Russell and Martin (2012) discussed the social dimensions of the two discrete locations and scales of bone grease manufacture at Çatalhöyük, where small-scale processing appears to have occurred in individual houses, whereas large-scale processing events which, from the scale of the debris deposited, would have required processors from multiple households, took place in public spaces, and perhaps was timed with seasonal slaughter of caprine flocks.

Since the 1970s, many zooarchaeological studies have used archaeofaunal materials to investigate socially situated actors, households, and communities and their activities. Despite the abundance of studies, few publications have explicitly articulated how to approach the range of topics involved in socially focused zooarchaeological research. It may be helpful to begin with the nested set of analytic frameworks presented in Chap. 3's Fig. 3.1. Research on social relationships focuses on one of the statistically determined, orders of systemic organization, but inferences in this area are necessarily linked to traces those made at simpler levels of determination.

25.1.1 Methods for the Toolkit: Familiar Means Applied to Novel Ends

Two pioneering writers on relevant evidence for social and economic relations, Reitz (1987) and Crabtree (1990) stressed that a social approach does not abandon workable methods used in other kinds of archaeofaunal research but rather incorporates and builds upon them, a point also stressed by zooarchaeologists working with complex societies, including deFrance (2009), Emery (2004), Landon (2005), O'Connor (2000), Orton (2012), Russell (2012), Reitz and Wing (2008), and this is evident in the work of others (e.g. Zeder 1991; Lapham 2005).

As advocated in Chap. 1, rather than trying to devise a step-by-step recipe for success in such research, we might consider that the best approach is to assemble a "toolkit" of methodological, conceptual, and theoretical approaches to address the ranges of research problems we expect to find. This section suggests methods and concepts that may prove useful for stocking such a toolkit, reiterating suggestions and examples of other zooarchaeologists in the process. Chapter 1 also noted that zooarchaeologists are a theoretically diverse lot, with varied ideas regarding how the world works and different theoretical approaches. The "toolkit" approach does not insist on a single approach at that level, but advocates that practitioners experiment with lower-order tools, only some of which are discussed here.

Zooarchaeologically investigating social relations combines methods that depend on uniform, process-product relations to specify archaeofaunal evidence with person-focused conceptual approaches. Crabtree (1990), who worked with historic archaeofaunas in Europe and North America as well as those of prehistoric complex societies, outlined three areas of interest for zooarchaeological research on complex societies: trade and exchange relations, social inequality, and ethnic distinctions. She outlined how these three topics can be investigated using zooarchaeological methods. Though she focused only on complex societies, Crabtree's proposals provide an excellent opening to considering methods for exploring social zooarchaeology in a wider sense. Those seeking updated views of specific topics discussed here are referred to Campana et al. (2010), deFrance (2009), Emery (2004), Russell (2012), and Landon (2005). The following sections treat each of these areas, but in a somewhat different order than did Crabtree, so as to accommodate discussion of groups a broader array of societies.

25.2 Social Inequality

Crabtree (1990) observed that status-related differences in access to animals and their products in complex societies can most readily be accessed when architecture, art, and even historical documents, supplement archaeofaunal and artifactual data. Among foragers and simpler food producers, such resources will be sparse to lacking, but investigating social relations with archaeofauna is not a lost cause. The following sections outline how archaeologists have explored social relations at several scales and quantities of available evidence.

Reitz (1987) and Crabtree (1990) noted that commonly used archaeofaunal indicators of status include: differences in the quality of cuts of meat (historically defined), as reflected in the elements and the diversity and proportions of species consumed. *Element frequencies* and *simple measures of relative taxonomic abundance* (MNI and NISP) have been commonly used. For non-historic cases, indices of food utility have produced interesting results, as has the refitting of skeletal elements and carcass parts. Nearly all the studies noted in this section apply some form of compositional analysis of spatially differentiated samples, be these temporary houses in a forager camp or permanent structures with different ascribes functions.

25.2.1 Social Zooarchaeology Among Foragers

Methods drawn from the zooarchaeology and ethnoarchaeology of hunter-gatherers have been applied productively to studying ancient foragers' social relations. These include *bone refitting, carcass refitting*, and *nutritional utilities*. I would add the tool of *return rates* for future use, because of the interesting results it has produced in a few cases (e.g. Thomas 2014). Where the first three have been applied, site context and content met certain prerequisites: optimal sites are single-component, without overlying archaeological materials, and have some vestiges of household structures, such as hearths or postholes. Bones must be well preserved enough to permit surface modification analysis and, in the case of carcass refits, measurement of diaphyses and other skeletal elements. In short, the site must fulfill requirements for *intrasite compositional analysis* of separate deposits. Not all assemblages are amenable to this kind of investigation (Enloe 2008). Highly comminuted assemblages, those heavily altered by taphonomic processes, massive middens containing remains of many individuals, and most stratified sites cannot be exploited using such methods. The following sections discuss these methods in the context of studies that have applied them.

Enloe (2003) reviewed the voluminous anthropological literature on food sharing, ethnoarchaeological observations of meat sharing, and archaeological attempts to retrieve such behavior. Works summarized underscore that discussions of meat sharing among foragers proceed from the assumption that, because mobile hunter-gatherers are "egalitarian," they share the yields of hunting larger animals equitably among all households in their encampments. But does this egalitarianism actually hold true, if one examines the distribution of nutritional values? Asymmetries in access that remain consistent over a season or longer may be reflected in the refuse of different households.

In one of his early papers, Frison (1971) used *bone refitting* in well preserved protohistoric Shoshonean house remains and features to explore the full spectrum of handling of pronghorn antelopes (*Antilocapra americana*), from primary butchery through culinary processing. In two of the houses, he refit diaphyses of broken long bones to assess whether any evidence existed for the sharing-out of food between their inhabitants, and finding no refits between houses, inferred that each household took carcass segments and processed them without further sharing. Frison noted no apparent inequalities between the houses in this small dataset (see O'Brien's analysis below).

Carcass refitting can be seen as taking bone refitting to another level. It was developed by Todd to monitor the subdivision of bison carcasses at the Horner Site, an early Holocene (Cody Phase) bison kill-butchery site in Wyoming (Frison and Todd 1987). After a ground-truthing study with museum specimens, Todd used measurements of preserved right and left long bone articular surfaces to match elements from the same animal and to monitor their distribution in space. In the case of the Horner Site, the study focused more on the mechanics of large animal primary butchery especially meat stripping and marrow bone fracture, rather than on the ultimate ends of this process in consumption.

Three more recent studies, one ethnoarchaeological and two archaeological, used *carcass refitting* and *nutritional utilities* to discern different households' access to animal foods within a larger social group. These suggest that, in the rare cases when houses and their associated debris are preserved, intrasite analysis of nutritional utilities may allow zooarchaeologists to see subtle asymmetries within these societies.

Waguespack (2002) combined *element frequencies* and *carcass refitting* with *meat and fat utility* analysis to explore sharing of carcasses at the Palagana Site, an historic nineteenth century Nunamiut settlement with known inhabitants in the Brooks Range, Alaska. Binford excavated the site during his ethnoarchaeological research and collected oral histories about the site inhabitants from older members of the Anaktuvuk Pass community. Palagana was still renowned among the twentieth century Nunamiut as a great hunter, whereas the male head of the other excavated household, Kapkana, was more known for his skills as an artisan than as a hunter. Waguespack analyzed the assemblages to assess if these supported one of two scenarios for carcass sharing in terms used in human behavioral ecology: variance reduction versus tolerated theft. Variance reduction is produced by continuous, generalized sharing among households that would even out the effects of any individual hunter's intermittent lack of success. Tolerated theft, a term taken from animal behavioral ecology, assumes that, when an individual monopolizing a resource has enough of it, the balance is less worth defending from others seeking it. Waguespack predicted that, over time, variance reduction would produce an even distribution of all types carcass segments among all households in an encampment. She predicted that tolerated theft would produce a less uniform distribution of carcass segments, with the "provider" household(s) retaining higher-utility body elements and giving away lower utility ones. Regardless of the terminology, the research concerns socially mediated transfers of animal parts.

Waguespack "refitted" individual caribou carcasses, using both metrical and nonmetrical traits, and tabulated %MAU and MNE for Kapkana and Palagana's houses. Waguespack inferred that most of the meat was flowing from Palagana's household to Kapkana's, with most skulls and anterior cervical vertebrae remaining in Palagana's household. Sharing was asymmetrical: Palagana's house had more innominate units, with a more even representation of lower forelimbs. However, "High general utility elements such as the femur, tibia, and humerus, which are rich in both meat and marrow, occur more frequently in the Palangana household and are significantly underrepresented at Kapkana's" (Waguespack 2002:410). She interprets the results as reflecting the tolerated theft model of sharing. Because caribou were generally shared among traditional Nunamiut, the ideology of equality and sharing is maintained between the houses. However, people as close to prey animals and their products as the Nunamiut would know which body segments were being withheld and their nutritional worth. This example of nutritional inequality between households in an "egalitarian" community's social subdivision of animal bodies could have real consequences for the households involved, if both included reproductive age women and growing children, where animal fats can influence health and survival. Waguespack quotes Binford (1991:101) on the role played by Nunamiut women in managing allocation of such subdivided carcasses.

> ... sharing out of stores is considered 'women's business' in that woman are generally responsible for removing meat from stores and for its disposition. This meat regularly circulates in winter camps largely in terms of female labor concerns... Thus a kind of demand pooling in the distribution of meat out of household stores is constantly occurring in winter camps.

Thus, the patterning discerned by Waguespack likely reflects the actions of women in Palagana's household, as part of culturally sanctioned practices of household economy.

Working with French Upper Palaeolithic archaeofaunas from Pincevent and Verberie, Enloe and David (1992, 1989) used carcass refitting and nutritional utility indices to explore the distribution of body segments from individual reindeer (*Rangifer tarandus*, known as caribou in North America). These open, laterally dispersed, repeated occupational occurrences in the Seine River Valley are extraordinarily well preserved, having been were covered soon after their creation by gentle overbank flooding (Leroi-Gourhan and Brezillon 1966, 1972). Margins of dwellings, hearths, flaking floors of the Magdalenian tradition, butchery and consumption zones are all apparent. See Zubrow et al. (2010), especially Audouze (2010) and Enloe et al. (2010) for further explorations of social dimensions of these and other sites.

Following Todd's strategy, Enloe and David established criteria for refitting using comparative museum specimens, then applied these to refit archaeofaunal skeletons and monitored distribution of individual animals among three houses at Pincevent, Level IV 2 (Enloe and David 1989, 1992). They noted that, while upper leg parts of all animals appear to have been distributed among all households, one household possessed a disproportionately greater number of high marrow utility metacarpals and metatarsals, whereas the other two had relatively few. They infer that one household preferentially retained marrow-rich elements, a permutation of what Waguespack saw in the Palagana site. Here again, an ideology of sharing was apparently enacted through the distribution of meaty body segments but not with fat-rich elements.

O'Brien (2015) reanalyzed Frison's (1971) Eden-Farson antelope assemblage, which had in the meantime been extensively studied by other researchers. Age structure analysis of the pronghorn dental sample (e.g. Lubinski 2013) clarified that the pronghorn, while probably from mass kills, are from multiple, seasonally differentiated events. O'Brien used carcass refitting methods based upon Todd's, but, heeding Lyman's (2008) warning that metrical criteria alone probably could not differentiate more than 15 individual animals, he used osteometrics to narrow the subsamples for visual comparison of potential bilaterally symmetrical matches (O'Brien and Storlie 2011). O'Brien then traced distribution patterns of individual carcasses segments among the ten excavated houses, concluding that, "The site boasts multiple refits between houses, but what is less clear is whether occupants shared certain skeletal elements more often than others and with whom" (O'Brien 2015:658). He also determined that smaller pronghorn carcasses were equally likely to be shared among houses as larger ones in the materials he analyzed, noting that historic records document sharing out of butchered animals from communal game drives. O'Brien notes that, while some households appear to have been more active sharers than others, none displayed preferential concentration of specific elements or body segments. In this paper, O'Brien did not assess marrow utility distributions.

These examples suggest ready to hand methodological tools with which to explore, certainly with benefit of contextual data, whether or not suitable archaeological occurrences display departures from the "generalized reciprocity" often attributed to mobile foragers.

25.2.2 Historic Archaeofaunas and Socioeconomic Difference

Relatively recent historic archaeofaunas have been analyzed using *element frequencies* and *taxonomic abundances* and interpreted using historically documented valuations of cuts of meat, but careful use of contextual information and interpretive caution is necessary. In her comparative analysis of archaeofaunal data from antebellum plantation sites in the southeastern United States, Reitz (1987) states that that many factors may alter any simplistic equation of "rich cuts = rich people." She notes that even plantation owning households seeking to spare cash reserves for other goals might have economized on purchased meats, resulting in modally more modest cuts of meat in their food refuse. Schmitt and Zeier's (1993) study of animal food refuse in an abandoned nineteenth century mining town in Nevada cautions against simplistic interpretations of high- versus low-ranking cuts of meat, while demonstrating what is possible with careful contextual analysis. Schmitt and Zeier consulted documents on occupations of inhabitants of different houses and assessed discarded ceramics for their indications of socioeconomic status, then juxtaposed these data with analysis of meat cuts in the same houses' refuse, with some initially paradoxical results. Casual laborers' and self-employed single males' trash contained ceramics generally correlating with their lower socioeconomic status yet some also yielded higher-ranked steak or roast bones. Schmitt and Zeier accounted for this by invoking the different outlooks and consumption behavior of workers in precarious employment circumstances week-to-week. They argued that such persons might "spend big" on meat when they had money, rather than rationalizing the distribution of resources over the entire span, as would middle class households with more predictable long-term incomes. This study underlines the importance of considering the wider *political economy* in which higher- and lower-ranking actors and households exist, including predictability of various households' incomes (deFrance 2009).

Milne and Crabtree (2001), as reported by Landon (2005), offer another instance of the complexity of assigning value to meat cuts in historic urban societies in their comparisons of cuts of meat from three residences in the Five Points area of New York City: a brothel, the home of a carpenter, and that of a rabbi. All were characterized by similar, inexpensive cuts of meat, despite residents' differences in social status.

Bartosiewicz (1997) cautioned against assuming that choices in meat cuts will invariably mirror their nutritional utilities because other cultural factors, such as the symbolic meaning of certain animals or cuts of meat, may determine selectivity. This criticism notwithstanding, it is worthwhile to use *utility indices* to explore the nutritional values of various skeletal elements in comparing assemblages, *precisely because* systematic departures from food utility rankings will reveal divergent systems of selectivity. I suggest that *return rates* for various animal and plant foods may also yield insights into social asymmetries. While these are usually restricted to calibrating forager dietary choices, in socially unequal situations, laborious food processing tasks are "outsourced" to members of lower-ranking groups or classes who may not consume the final product, except what they may surreptitiously capture during food preparation. In such cases, return rates can put a very real measure on the nutritional value that such compelled labor produces for the privileged class, and how much it may have cost the preparers.

Excellent studies of dietary differentiation in ancient Mesopotamia and adjacent areas, ancient Rome and its far-flung colonies, Medieval Europe, and more recent situations are numerous, and only a small selection is offered here. I refer readers to Russell's *Social Zooarchaeology* (2012), Landon (2005), deFrance (2009) as sourcebooks for a wider sample.

25.2.3 Institutionalized Inequality in Slave-Holding American Sites

Many zooarchaeological examples now exist from the United States' antebellum South, which not show only divergences in slave versus slave-owner diet, but also offer insights into how captive persons of African descent actively provisioned themselves. On slave-owning plantations in what eventually became the United States, zooarchaeological research on inequality is enabled by the spatial and architectural correlates of the white supremacist ideology that emerged in the seventeenth and eighteenth centuries. Among its main tenets was spatial separation of living quarters for African-descended slaves from those of white slave owners (Vlach 1993). This architectural and spatial distinction had not been made in sixteenth century Virginia settlements, where slaves, European indentured servants, and masters often shared common living space (Emerson 1988), nor in Spanish Colonial Florida, where persons of different ethnic origins and statuses often resided under one roof (Deagan 1983). Thus, the seventeenth to nineteenth century political economy of the Anglo-American South, its ideological underpinnings, and the social worlds it created, differ from other slave-owning economies elsewhere in the Americas, which should be borne in mind by zooarchaeologists working on slave establishments in different areas.

McKee (1999) noted the tension between spatial separation of slaves from masters and the masters' need to keep watch on slave activities. Moreover, owners' need for slave labor in their homes maintained steady contact between persons with different racialized identities. Whether the slave quarters were in view of the "big house" varied, but the separation of food preparation, consumption, and other activities of daily life allow archaeologists to identify the outputs of masters' households versus those of enslaved persons.

With the Cannon's Point Plantation in coastal Georgia, Fairbanks and Mullins-Moore (1980) pioneered the use of *taxonomic identifications* and *element frequencies* in archaeofaunal samples from different contexts to explore dietary differences arising from divergent access to food and freedom of movement of the owners, overseers, and slaves. Otto (1984) offered a fuller treatment of the Cannon's Point

Plantation faunas. When the same domestic species were recovered from owners' versus slave middens, element frequencies reflected the retention of high-prestige leg and back segments for roasts in the owners' homes, whereas body segments used for stews dominated the slave refuse. Slave-owners' middens contained remains of deep-sea fishes, which could only be obtained using seaworthy boats, whereas slave food refuse yielded nearshore fish species requiring no watercraft. Many were readily caught on set-lines that could be visited before or after the workday. Remains of wild animals that could be caught in set traps, such as raccoons, were more common in slave quarters. Overseers, mainly white, working-class field supervisors of slaves, had food waste very similar to that of slaves, suggesting similar food preparation among lower status persons, despite many other divergences in their statuses and rights.

McKee (1999) analyzed plantations in the Chesapeake region, Virginia, stressing recent historians' emphasis on enslaved persons' social initiatives and negotiations within the plantation social order, especially regarding food supply. McKee had little bone debris to analyze, the product of "broadcast" refuse disposal and soil chemistry, so he turned to planters' ledgers for insights into dietary regimes and slave initiatives. Ledgers record slave rations only, however, reading between the lines, McKee discerned hints of slaves' providing for themselves. One master complained of the consistent disappearance of young pigs put out to forage in the woods just before the shoats had reached marketable age. Another journal entry recorded resentment at being pressured to buy the dried fishes slaves had caught and prepared in their spare time, which after their purchase were allocated as part of slave provisions later in the year. McKee stresses that self-provisioning may have not only been a necessity for healthy fat and protein supply but also served as a means to subvert social order and renegotiate power, stopping short of outright rebellion or running away.

At Thomas Jefferson's Monticello, Crader (1984, 1990) initially discerned the expected master-slave distinctions in bone refuse but later found what appeared to be status differences among slave households. The "Dry Well" sample, refuse from the Jefferson household itself, displayed more mutton and bones from roasts with slicing marks typical of carving than did the "Storehouse" slave quarter sample, which yielded relatively more pig and stew meat type bones. Discarded artifacts in the two middens also reflected differences in consumption, with liquor bottles and porcelain in the Dry Well deposit and coarser ceramics in the Storehouse sample. However, the "Building O" sample, listed as slave quarters in plantation records, yielded some carved roast bones and porcelain wares, albeit slightly damaged and mismatched. Jefferson's plantation records do not record names of persons living in the slave quarters, but Crader speculates that this household had special links to the main house. Given the ongoing interest in the relationship between Sally Hemings and her family and Thomas Jefferson (e.g. Gordon-Reed 2008), Building O's evidence offers food for thought. However, it is equally possible that it was the residence of Jefferson's cook, or of his personal manservant Isaac Jefferson, whom Jefferson later freed. In any case, this study serves to caution against simplistic assumptions about a generic "slave" category when analyzing archaeofaunas from such contexts.

25.3 Trade and Exchange Relations

Given her broad experience with archaeofaunas from differently structured polities, Crabtree (1990) approached exchange relations by asking how, in societies with at least the possibility of occupationally differentiated roles, persons who did not acquire or own animals obtained them as food. To address this question, she proposed investigating four topics that zooarchaeological methods can address:

1. Ascertaining whether specialized producers exist;
2. Identifying sites of producers and consumers;
3. Establishing what animal foods were available to consumers;
4. Determining how animal foods are distributed to consumers (e.g. centralized distribution vs. market).

These topics and the methods used to investigate them are discussed below.

25.3.1 Ascertaining Whether Specialized Producers Exist

Element frequencies have been shown to aid in discerning the function of sites as well as the transport of selected cuts from slaughtering houses and markets (points 1., 2., 4., above). Roman colonial and Medieval in England cities have yielded locally dense concentrations of axial skeletal parts, interpreted as by-products of slaughterhouses (Crabtree 1990, 1996; Maltby 1984; O'Connor 2000). Zeder (1991) used taxon and element frequencies to infer function for different sectors of the city of Tal-e Malyan, Iran.

Species abundance measures and age-specific *mortality profiles* (Chap. 22) may also aid in identifying the existence of specialized producers at a remove from the center at which skeletal elements came to their final resting places. O’Connor (2000:163) notes that sheep and cattle slaughtered and consumed in medieval York were fully into adulthood when supplied to the town, opining that these were probably surplus animals in herds and flocks managed for other dominant uses to their owners, such as traction, milk, or wool. Thus, meat supplies to the city not come from producers solely specializing in that market. Wapnish and Hesse (1988) found meat supply to Tell Jemmah, a Middle Bronze Age site in Israel, consisted mainly of caprines under 1 year or over 5 years, which they interpret as surplus animals in a milk-producing economy.

25.3.2 Identifying Locations of Producers and Consumers

Age-specific *mortality profiles* (Chap. 22) can aid in defining site or sector functions as well as supply practices (1., 2., 4.). Some zooarchaeologists have used osteometrics to distinguish females from males (Chap. 6.), permitting finer focus on how large-scale production was managed. Reliable *age and sex determinations* (Chaps. 6 and 7) are fundamental to studying age- and sex-specific slaughtering patterns, with methodological problems already discussed. However, because much age-specific slaughtering in ethnographically documented herding systems takes place before the culled animals are fully mature, dental eruption and epiphyseal fusion schedules can be used to determine age-at-death for a great number of specimens produced by such systems. Examples can be found in Stein (1987) and (Zeder 1991). Articles in a special issue of *European Journal of Archaeology* (see Valenzuela-Lamas & Albarella 2017) on animal husbandry in the Rome's western European Empire illustrate the use of multiple lines of zooarchaeological data in combination with other environmental, architectural, and historical evidence to discern animal production systems at a regional scale.

25.3.3 Animal Foods Available to Consumers

The types of animal foods available to consumers can in part be investigated by archaeofaunal samples' *relative taxonomic abundances* and *diversity* (Chap. 22), which are best assessed in the context of a regional sample of sites for comparison. Multiple studies have shown that species diversity of Southwest Asian urban animal food supply was lower than that of contemporaneous sites in the countryside (Wattenmaker 1987; Zeder 1991). This was also the case for some medieval European towns and cities, but not for others (Crabtree 1990:160). Reitz (1986) noted that the port city of Charleston, South Carolina was located in rich lowlands that hosted a diversity of estuarine, marsh and terrestrial native species, many of which found their way to the kitchens and tables of all classes.

25.3.4 Determining How Animal Foods Were Distributed to Consumers

Crabtree (1990) stressed that standardized *butchery mark* patterns may be useful in discerning specialized slaughter and butchery in the production of meat for market, but that this aspect of assemblage analysis has not been fully explored. Peck's (1986) study of Roman villa archaeofaunas in England revealed some where cattle were butchered highly consistently, while other villas' samples displayed haphazardly placed marks. He inferred that the first reflected regular, expert butchery of cattle, and the second only occasional butchery of cattle by inexpert processers. Theoretical and methodological approaches to butchery more recently were explored by Seetah (2008). Contrasts between sawing and hacking marks are sometimes seen in Spanish colonies, where saws, the traditional carcass segmentation tools of European butchers, were at a premium (Reitz and McEwan 1995), and in the treatment of stew meat segments given to slaves by their owners (Reitz 1987).

For distinguishing longer-distance trade in exotic animals or their products, Crabtree cited *taxonomic identification* and *relative abundance* data as key. Examples of elite acquisition of exotic animal foods abound for Imperial Rome and Medieval Europe, and Ervynck et al. (2003) offer a discerning discussion of exotics in such archaeofaunas. Trade in exotics may involve species not used as food, instead transferring ideologically significant animals to be sacrificed and placed in ritual deposits. The Great Temple of the Aztec capital, Tenochtitlán, in what is now Mexico City, has tropical mollusk shells, fishes, crocodiles, and rainforest jaguars interred as foundational deposits and as later, special offerings (López Luján et al. 2012; Polaco 1991).

Tracing such long-range exchange in archaeofaunal exotics has been enhanced by stable isotope analysis, especially strontium and oxygen isotopes for taxa moving from region to region (Chap. 22). Puebloan peoples in the American Southwest acquired and bred macaw parrots, and these trade relations have again been elucidated by isotopic analysis (Minnis et al. 1993; Somerville et al. 2010). Genomics now is also helping archaeologist trace the transfer diffusion of domestic animals, as was the case with European swine cited in Chap. 23 and has been useful in understanding the geographic sources of Polynesian colonists and their pigs in their voyage through Oceania (Larson et al. 2007). Both stable isotopes and genomics have helped zooarchaeologists disentangle the complex histories of domestic turkeys and their spread in Mesoamerica (Speller et al. 2010; Thornton et al. 2012).

25.4 Ethnic Distinctions

Since the 1970s, historic and prehistoric archaeologists have sought to explore the cultural differences we call “ethnicity,” using evidence from architecture, space use, artifacts, and some cases, archaeofaunas (Deetz 1996; Deagan 1983; McEwan 1989). Anthropological archaeologists should appreciate that ethnicity comprises social categories produced and reinforced by practices within and without the defined group. The history of the Americas shows that new ethnicities have repeatedly emerged in colonized regions, as people from indigenous and colonizing groups produced offspring who sometimes formed new political identities, as with the concept of *mestizaje* as a basis for social identity in Spanish colonies (Deagan 1973) or when culturally diverse, self-liberated groups of Africans formed their own new societies. Much recent work on ethnicity has emphasized differences in everyday practices, including foodways, as forms of intentional identity maintenance and political resistance (Gumerman 1997).

Given ethnic diversity in the selection and use of foodstuffs, variations in food preparation, and divergences in consumption practices in pluralistic societies today, it is not surprising that zooarchaeologists have tried to investigate “ethnic food” as a way of identifying different communities within larger-scale societies in the past. Archaeologists approached such archaeofaunas with the expectation that distinct ethnic groups within a larger society would by preference use different food species, favor divergent cuts of meat from the same species, and engage in disparate methods of preparation.

However, both in Eurasia and the Americas, faunal remains have often proved to be problematic indicators, whereas associated artifacts and, in some cases, architecture, were better markers of the presence of a distinctive ethnic group within a larger settlement (Crabtree 1990; but see Atici 2014 for a textured reading of multiple lines of evidence). The question of why this has been the case is worth exploring in more detail, as it probably entails how animals and other foods were implicated in the political economies of past societies. This may result from several causes. Post-consumption refuse disposal in settlements of urban scale may blur distinctive patterns of butchery, culinary practices, and consumption. The political economy of a region or city may also be an important determinant of these outcomes. Zooarchaeologists must demonstrate rather than assume that ethnic enclaves had their own meat supply chain, instead of than being part of a larger supply system controlled by the dominant social group. In the latter situation, unless the ethnic enclave could obtain entire animals, the dominant group's butchery practices will determine the cuts of meat available to them. Chickens or ducks might indeed have been acquired whole, but larger mammals might be prohibitively expensive and impractical to preserve. Such embedded meat supply chains might explain the lack of departure from the Anglo-American norm in bone refuse from multiple Chinatowns that Gust (1993) studied in the greater U.S. West, while artifacts from the same sites definitely indicated Chinese foodways and consumption patterns.

25.5 Conceptual Tools for the Toolkit

The forgoing section made clear that, with the exception of isotopic and genomic analyses, productive tools for the zooarchaeological toolkit investigating social relations with archaeofaunas are the "old school" zooarchaeological methods often developed in other contexts. Later reviews of social zooarchaeology, whether or not of complex societies, (Emery 2004; Landon 2005; deFrance 2009) routinely use the standard units of quantification and comparison reviewed by previous chapters. If one is interested in studying social relationships, that's the good news. It's also the bad news, because each one of these methods comes with its own challenges. The recommendation is to use them thoughtfully.

When these methods are applied to explore socially grounded relationships, the novel part may be the different conceptual tools that allow one to use analytic methods developed in other contexts to elucidate social relations and roles. Although quite a few notable zooarchaeological studies have shown these conceptual tools "at work," few explicit discussions of their use exist in the literature. It is hoped that the following one will prompt some critical interest. Like real tools in a toolkit, these are a bit of an assortment, included not for their coherent interrelations but for their individual utility in different situations.

25.5.1 Conceptual Tool: The Household

"Household archaeology" shifts the analytical perspective from the individual to the social context of much decision-making in human societies. Households are a pervasive phenomenon among anatomically modern humans, being the smallest organized unit of society from foragers to urban dwellers. Most often composed of co-residing persons who are also members of a reproductive unit, they may be multigenerational, include non-kin, and may comprise individuals entirely unrelated by marriage or descent, as with Medieval convents and monasteries or contemporary co-residing urbanites trying to save money on housing expenses. In small-scale societies, households are the basic economic and reproductive units, pooling labor toward common goals, sharing and redistributing resources, preparing and consuming daily meals together. Precisely when this novel social formation emerged in hominin history is controversial, but all agree this social trait separates us from our closest primate relatives.

The concept of the household been broadly employed in history and historical demography (Laslett 1969), sociology (Bonney 1988), and anthropology (McCabe et al. 1982; Wilk 1989; Moberg 1985; Paolisso et al. 1999; Curry et al. 1996; Flannery 1976; Kent 1990; Sheets 2000; Sullivan 1987) as a means of studying small-scale decisions that affect broader communities and regions. It has been critically examined (Yanagisako 1979; Netting et al. 1984), with the caution that their ubiquity should not be assumed to reflect uniformity in composition nor in the fundamental cultural propositions (Joyce 2000) validating them. Archaeologists have deliberately sought the physical evidence of households since the emergence of processual archaeology (Allison 1999; Curry et al. 1996; Flannery 1976; Gargett and Hayden 1991; Huelsbeck 1989; Kent 1990; Reed and Niles Henlser 2001), and more recently some have sought to critically refine this concept by focusing attention on the gendered nature of relationships and work within domestic groups (Hendon 1996; Tringham 1991; VanderWarker and Detwiler 2002; Joyce 1992; Junker et al. 1994).

To explore animal uses within and among households, zooarchaeologists assess whether the archaeofauna under study lends itself to the *compositional analyses* outlined in Chap. 15 and developed by Russell (2012:371-392). Preliminary studies of contemporary smaller-scale communities, historic, and archaeological sites outlined in Chap. 15 and this chapter suggest this is, with some site conditions, a realistic goal. For settlements inhabited for some time, household primary refuse is likely to be present as microvestiges, plus secondary refuse deposits. These approaches have been developed in considerable detail with the aid of practice theory (see Sect. 25.5.6) at Çatalhöyük by zooarchaeologists and paleoethnobotanists (Bogaard et al. 2009; Twiss 2012; Hastorf 2012). They have used spatial context, associated artifactual and architectural features, evidence from human remains, and comparative compositional analysis to explore differences between domestic meal deposits and those created during community feasting, and discussed the tensions that may have attended life in this large settlement. Archaeological recovery strategies that permit compositional analysis in relation to contextual evidence are a productive means of exploring social relationships, even into the late Pleistocene, e.g. *The Magdalenian household* of Zubrow et al. (2010). Examples from Pollock's (2012) *Between feasts and daily meals. Toward an archaeology of commensal spaces* further illustrate the range of data and conditions of recovery that enable household- and community-scale analysis.

25.5.2 Conceptual Tool: Chaîne opératoire

This concept has been so thoroughly discussed in other chapters (Chaps. 15 and 20) that here it suffices to say that socially embedded actors with identities, rights, and responsibilities participate in such operational chains.

25.5.3 Conceptual Tool: Task-Differentiation

The task-differentiation perspective, first articulated by Spector (1982) in her work on Plains Indian archaeological materials and later advocated as an aid to studying social relations and gender (Conkey and Spector 1984; Spector 1993), offers an interesting complement to the *chaîne opératoire* approach. As presented by Conkey and Spector (1984:25), tasks are necessarily delimited, socially coordinated, and gendered:

As presented by Conkey and Spector, the task-differentiation framework highlighted dimensions of male and female activity patterns. The assumption underling this orientation is that what age- and gender-differentiated people do – how they are socially, temporally, and materially organized – is achieved by and hence directly related to the types and structure of sites and their "contents" that are the archaeological record. The framework focuses attention on four interrelated aspects of task performance: the social, temporal, spatial, and material dimensions of each task undertaken by any given group.

Although Conkey and Spector did not do so, the task differentiation approach can be integrated with *chaîne opératoire* approaches. The latter focuses on the mechanical operations with a material that persons must sequentially accomplish to produce useful outcomes, while the former stresses the actors and the social relationships that coordinate such temporally sequenced operations. The task differentiation approach adds to *chaîne opératoire* analysis the question of which and how many social actors may have accomplished steps in production, and whether these are likely to have been the same persons from one step of the chain to the next. It views the products as socially contextualized goals.

The task-differentiation approach produced rich results when supported by direct historic analogies such as Spector (1993) used in her work on pre-contact Lakota in Minnesota. These allowed her to assume that specific tasks were differentiated by age, gender, and reproductive status. Brumfiel (e.g. 1991) applied a similar approach in her research on women's and men's work in Huexotla, Mexico, before and after imposition of Aztec imperial control over production. However, most zooarchaeologists do not work with archaeofaunas possessing the strong historic continuities with documented cultures that Spector and Brumfiel mobilized. They thus lack similar networks of analogies to use in assigning social groups to specific roles. Whether a task-differentiation approach can be used without essentializing age or gender roles is an open question. Behavioral ecological research with contemporary foragers has demonstrated great diversity in levels of foraging energy expended by different genders and ages (Bird and Bliege Bird 2000; Hawkes et al. 1989, 1995; Bliege Bird and Bird 2008). These warn zooarchaeologists to think carefully about considering the task-differentiation approach in such circumstances, but if nothing else, simply recalling that the human "actors" who produced and modified the archaeofaunal sample under study were likely of different ages and genders can open one's mind to the potentialities of the data, as was the case with Hastorf's (2012) question, "What was the place of the cook?" at Çatalhöyük, the answer to which was quite unusual.

25.5.4 Conceptual Tool: Political Economy

The phrase "political economy" has some antiquity in economics and refers to the interrelation of political policies and practices and economic processes, which together influence social institutions and individuals. Although Gumerman was not explicitly defining foodways in relation to political economy, his abstract encapsulates food related practices within such a matrix:

> The food system not only involves what is consumed but includes the labor and technology that goes into the production and preparation of food as well as how certain foods are distributed and their waste eventually discarded. Food systems within and among complex societies are thus tightly intertwined with social differentiation and the political economy and participate in defining and maintaining differential social relations (Gumerman 1997:105).

De France (2009) argues that archaeofaunal data from a complex society are only coherent when understood within the political economic framework of that society, a point already made in the section on ethnic differences in animal processing. Depending on the age and documentation of the site, such information is available to zooarchaeologists from the findings of other researchers, from historic records and other documentary sources.

25.5.4.1 A Zooarchaeological Case in Political Economic Perspective: Missing Livestock

Crabtree (1990) cautioned that archaeofaunas recovered from single sites that were actually part of a regional economic system may not transparently reflect the overall economy, but rather simply animals people ate in that locale. This was the case at

Mott Farm, an eighteenth century Rhode Island farmstead (Bowen 1975), and at medieval Kirkstead Abbey (Ryder 1959). Historic records for both sites indicate wool production was the dominant activity involving livestock, yet the remains of other domestic species were more common than those of sheep in dietary refuse. Such cases raise the specter of vexing and insoluble interpretive problems. If one has no historic records on economy, how could one tell whether a local faunal assemblage reflected the overall animal-based economy? In this situation, it is clear that bones are truly not enough, and that other markers of specialized, intensive secondary product economies should be sought among artifacts, features, structures, site hierarchies, and any other relevant evidence.

25.5.4.2 A Zooarchaeological Case in Political Economic Perspective: Food Taboos

The origins of religious taboos on pork consumption by both Judaism and Islam has been the subject of extended debate, drawing in public health, climate, and other factors (Harris 1989; Ryder 1994; Diener and Robkin 1978). Genetic and archaeofaunal evidence indicate that pigs were independently domesticated in Southwest Asia (Chap. 22), from where they spread to the Nile Valley as far south as Sudan. Abundant pig remains are found in Neolithic, Chalcolithic, and early Bronze Age towns and cities, and only in the later Bronze Age did they begin to disappear from ancient sites (Hesse 1990, 1995). Zeder (1998) argues that, as a native animal, the pig is well adapted to region, and that no change in regional climate or ecology appears to have triggered this shift. As Bronze Age state bureaucracies consolidated control over pastoral herds of cattle, sheep, and goats, either by declaring direct royal ownership or by taxation of trade in these animals, pigs presented an administrative problem. Unlike the ruminants foraging outside city walls, pigs can live in urban households' backyards, transforming household waste into meat and fat. Backyard pigs reproduce swiftly and might never enter the market before slaughter, thus sustaining urban meat self-sufficiency under a regime of meat taxation. Zeder (1998) argued that a state-sponsored ideological shift that labeled pigs as unclean and their consumers as community outcasts would serve the ends of state taxation systems, creating a legacy of aversion transmitted to later monotheistic religions of the region. Russell (2012: 34-38) offers a fuller discussion of this topic.

25.5.4.3 A Zooarchaeological Case in Political Economic Perspective: Seasonal Farm Work

From her systematic study of eighteenth century Connecticut farm account books and probate records, historic zooarchaeologist Bowen (1988) concluded that, contrary to most historical portrayals, these New England farmsteads were far from self-sufficient. Bowen argued that patterns of slaughtering, preservation, and household-based production of secondary products can only be understood when seen in the context of the farmsteads' documented labor needs, and the means they used to meet them. Casual and contract laborers – local men lacking land of their own – were essential to farmsteads' seasonal production peaks, as was an individual farm's reciprocal reliance on other farmsteads for more highly skilled collaborators during peak seasonal demands, including food preservation work. Bowen found that laborers were often partly paid in fatty animal products – butter, cheese, and bacon, whereas farming households often exchanged high-value preserved meats such as hams, as amicable gestures between peers that solidified friendly relations and reciprocal cooperation.

Bowen used principles drawn from the meat science to explain how the timing and pattern of slaughter and preservation of different domestic species result from tradeoffs that farmers made among other work demands of the farmstead, the differing shelf-lives of beef, mutton, pork, and poultry, and the heavy skilled labor demands involved in preserving dairy products. Although Bowen did not stress gender, she notes that the work invested in preserving various meats and milk products, and the systems of knowledge of preserving each food type, were women's realm. Bowen's study stands as fine application of knowledge of the intrinsic properties of various species' meats within a historically grounded political economic framework.

25.5.5 Conceptual Tool: Practice Theory

With its focus on the cultural underpinnings of habitual practices within spaces, from domestic to neighborhood to larger urban zones, *practice theory* (Bourdieu 1977, 1990; de Certeau 1984; de Certeau et al. 1998) offers archaeologists useful intellectual tools. If we proceed from the assumption that most "patterning" in archaeological materials was produced by recurrent, habitual actions, then we can ask how this aggregate patterning reflects socially and culturally structured practices. With some rethinking to integrate it with the distinct way that archaeologists infer from evidence of past human actions, this body of theory has provided a useful tool for rethinking larger-scale "structures of everyday life" (Braudel 1992) in various communities. This has been thoroughly explored and developed in relation to artifacts and their production (e.g. Dobres 2000; Cordell and Habicht-Mauche 2012; Dietler and Herbich 1998), but less widely in general zooarchaeology (but see Marciniak 2005a; Bogaard et al. 2009). I have recently argued (Gifford-Gonzalez 2014) that practice theory can help us reinvigorate our analytic approaches to some of our basic zooarchaeological sources, especially refuse deposits or middens.

Because theories of agency differ in the degree of freedom of action they assume, archaeologists should identify their own position with respect to constraints on action posited by different practice theorists. Joyce and Lopiparo (2005) caution that, among the French theorists who originated practice theory, some notable differences exist. Whereas Bourdieu appears to believe that only truly monumental events persuade people to shift from their *habitus*, de Certeau and his colleagues espoused a view of everyday practice that allowed not only for small variations on a theme but also for the possibility of more radical, intentional departures from *habitus*.

Document-aided archaeological researchers have used practice theory as a tool to explore aspects of agency in both historic and earlier times. For example, Lightfoot et al. (1998) explored interethnic relations and literal community-building among indentured Native Alaskan male hunters and their female Kashaya Pomo or Coast Miwok partners at the Russian colony of Fort Ross, in north-central California. The archaeological evidence was read with attention to the everyday practices of space use, house-building, cooking, housework, and refuse disposal, each seen through the lenses of the habitual practices on the part of the ethnic groups who contributed members to this settlement.

Other notable *zooarchaeological* applications of practice theory approaches have mainly been in Europe and Southwest Asia, including the Çatalhöyük examples noted earlier. Some in fact anticipated the explicit choice of practice theory as a theoretical touchstone, for example, Richards and Thomas's (1984) work on the Durrington Walls bone deposits. Later work applying practice theory to unusual deposits of animal remains has interrogated the concept of "ritual," arguing that this should not invariably be interpreted as demarcated religious enactments, but rather that redundant patterns of placement of animal remains in deposits may express the "rationality" of everyday life, as well as exceptional practices (Brück 1999; Stahl 2008).

25.5.5.1 A Zooarchaeological Case in Practice Theory: Linear Band Ceramic Deposits

Marciniak (2005a, 2005b) presented a meticulous zooarchaeological analysis of six Neolithic Linear Band Ceramic (c. 5600–4750 BC) sites, relying on the concept of *habitus* to explore animal consumption and refuse disposal practices. Asserting that people enacted their social identities through animal foods, just as much as when constructing their distinctive longhouses, Marciniak (2005a:148) stated:

> Concentration upon taken-for-granted routines of daily life can give insight into the ways in which Neolithic groups depended upon institutions, beliefs, and traditions they participate in and at the same time transformed and modified these constituent principles and rules.

Marciniak defined three categories of modification:

1. Dismemberment, skinning or filleting-related: cuts, chops, fractures;
2. Culinary related: pot-sizing chops and breaks with redundant patterning on the same elements;
3. Thermal and consumption-related: heat alteration before marrow and pulp extraction.

His study was based comparative, intrasite *compositional analysis* of refuse deposits, with detailed documentation of bone surface modification and taphonomic evidence. It revealed that pits around the long houses, themselves having divergent origins or functions, consistently received different animal taxa. Sheep and goat consumption was "usually in the house or directly around the house, and bone remains were deposited in pits around their entrances" (Marciniak 2005a:152). Remains of wild animals, along with wide range of artifactual refuse, both were placed into so-called storage pits. Remains of cattle, by contrast, were deposited in neither of these receptacles but only in "clay pits" that lay between long houses, pig remains were preferentially placed, as well. Moreover, settlement inhabitants a consistently placed a biased selection of cattle skeletal elements into the clay pits: head and neck units and plus other axial elements, but no leg elements. Similar patterns of disposal held true for refuse disposal in all six sites, which are widely dispersed in Poland and Slovakia. Marciniak's study demonstrates that an approach based in theories of agency can be applied to archaeofaunal materials excavated over many years, with varying recovery standards. Microvestige analysis would have been impossible with most such assemblages, but it demonstrated that, at grosser levels the archaeofaunas revealed much about structured handling of animal bodies.

25.5.6 Practice Theory and Middle Range Theory

To my knowledge, with the exception of Joyce's "Practice in and as deposition" (2008) and my own "Thoughts on a method for zooarchaeological study of daily life" (Gifford-Gonzalez 2008), few have articulated the connection between approaches based in practice theory and what we still call middle-range theory – to which this book has been devoted. To be clear, I am not asserting that archaeologists taking agency-based approaches have actually avoided using middle-range theory: it certainly underlies the work of Lightfoot et al.'s (e.g. 1998) approaches with the Fort Ross materials, Marciniak's above-cited research, and that of multiple researchers, including Marciniak, at Çatalhöyük. Most archaeologists simply get on with their interpretive work, without explicitly addressing the relation of the one to the other.

At the risk of belaboring the obvious, I discussed linkages between agency-based approaches and those based on research into determinative, "uniformitarian" relationships of materials that humans handle. Although *habitus* may be culturally and psychologically embedded, some choices in habitual practices are strongly determined by the demands of the materials with which actors worked (Gifford-Gonzalez 2008:18):

> Some materials – clays, metal ores, animal bodies, plant structures, etc. - require specific types and sequences of handling to produce desired outcomes. These determinative relationships of practice – when materials dictate human action to one extent or another, and sometimes to a specifiable degree – are important because they permit us to delimit other outcomes of habitual practice which are *not*, in any obvious way, driven by the same 'uniformitarian' constraints. In the process, what we can plausibly know about the deep past – the challenges any human being would face in handling certain materials, regardless of the details how they rise to those challenges – allow us to construct a more densely textured 'lived past' (cf. Stahl 2001:19-40).

Such a perspective implicates a *chaîne opératoire* approach. For zooarchaeology, one might seek to more closely stipulate the material parameters of each aspect of culinary practices, as outlined by Montón Subias (2005). This may permit insights into trade-offs that individuals and households faced in satisfying the basic demands of the human body, those of the animals and plants they acquired or managed, and those imposed the materials they manipulated, all the while engaging personal or corporate projects that required energy and time investment. Exploring those potentially conflicting demands facilitates more warranted views of past people's possible options and choices, and tends also to converge toward approaches taken by behavioral and reproductive ecology. Summing up, "Interpretation is thus not dictated by uniformitarian relationships, it is *enabled* by them" (Gifford-Gonzalez 2008:18).

25.5.6.1 A Zooarchaeological Case in Practice Theory: Reframing Refuse

As noted earlier, I reframed my own longstanding views of the early East African pastoralist (c. 1000 B.C.-A.D. 800) "middens" that yielded the archaeofaunas I analyzed, using de Certeau's and his colleagues' practice theory, in combination with ideas drawn from Douglas's classic, *Purity and Danger* (2002[1966]; Gifford-Gonzalez 2014). de Certeau's approach explicitly discusses the social matrix in which *habitus* is enacted, the communal pressures enforcing what his colleague Mayol (1998:8–9) called "propriety" – mostly unarticulated but deeply understood limits to one's actions within one's "neighborhood" – or just as readily, camp, village, etc. Mayol (1998:8–9) argued that, by tacitly consenting to social limits in speech, gesture, or behavior, dwellers consented to the "price to pay":

> …the dweller becomes a partner in a social contract that he or she consents to respect so that everyday life is possible. "Possible" is to be understood in the most banal sense of the term: not to make life "hell" with an abusive rupture of the implicit contract on which the neighborhood's coexistence is based. The compensation of this coercion for the dweller is the certitude of being recognized, "well thought of" by those around one…

While de Certeau and colleagues see free play and innovation as possible, within the limits of propriety, those limits are socially enforced. But what else motivates individuals enacting *habitus*? A half-century ago, Douglas challenged well-worn anthropological dichotomies that characterized "primitive" practices as motivated by "irrational" ideas of purity and danger by juxtaposing these with British notions of order and cleanliness. She asserted that, while ethnographic practices may appear irrational, so do British enactments of tidiness. It is simply a happy accident for those interested in trash dumps that Douglas exemplified her useful concept of *efficacy* with acts of cleaning up. Efficacy, then, is both socially contextualized *and* deeply internalized in practice.

> If we can abstract pathogenicity and hygiene from our [British] notion of dirt, we are left with the old definition of dirt as matter out of place. This is a very suggestive approach. It implies two conditions: a set of ordered relations and a contravention of that order. Dirt, then, is never a unique, isolated event. Where there is dirt, there is system… We can

> recognise in our own notions of dirt that we are using a kind of omnibus compendium which includes all the rejected elements of ordered systems… In short, our pollution behavior is the reaction which condemns any object or idea likely to confuse or contradict cherished classifications (Douglas 2002: 84–85).

Douglas (2002 [1966]:84) foreshadowed practice theory approaches in stating, "…instrumental efficacy is not the only kind of efficacy to be derived from their symbolic action. The other kind is achieved in the action itself, in the assertions it makes and the experience which bears its imprinting" (Douglas 2002: 84).

Combining these perspectives, everyday acts *perform* grammars or "rationalities" of household and settlement maintenance that are social enforced. I will repeat here what I said to a mainly Africanist readership (Gifford-Gonzalez 2014:355).

> As visible products of a highly managed and oft-repeated type of human action, refuse deposits communicate the state of community or household order... they are a recursively renewed form of communication, to the community and the knowledgeable stranger alike. Rephrasing a postprocessual truism about artifacts: refuse disposal enacts, rather than simply reflects, cultural and social relationships.

This view of trash dumps as culturally constituted, socially embedded enactments bridges to the materials with which archaeologists deal. Without presuming to read cultural meanings into disposal patterns, it allows us to explore the structured material outcomes of decisions about inclusion, exclusion, and placement that produced archaeological deposits, using common zooarchaeological tools.

In the early pastoralist case, I noted that multiple sites testify to disposal practices that mixed at least four classes of material – flaked stone, ground stone, ceramics, and bone without preferential taxonomic or element selection – into dense deposits covering many square meters. This pattern diverges markedly from that produced by documented pastoralist housekeepers in the same region, who deposits refuse in small dumps less than a square meter, spatially tied to individual houses or house clusters. Thus, in early pastoral settlements, waste disposal was very publicly visible and habitually corporate, differing remarkably from all known modern cases.

Other divergences have also manifested through zooarchaeological analysis. Early pastoralist sites such as these have yielded cattle that are larger than modern East African cattle, and their modal ages at death cluster around the attainment of full body size, rather than considerably earlier, even in more subsistence-oriented groups (Marshall 1990). Proportions of cattle to small stock are higher in early pastoralist groups, and recent stable isotopic work by Janzen (2015) indicates that both cattle and small stock, especially sheep, were managed very differently than in historically and ethnographically documented pastoralist groups in the region. Thus, understanding maintenance activities such as refuse disposal as *habitus*, reveals another way in which the first herders in the region differed from those encountered by Europeans.

25.6 Summing up the Toolkit for a Social Zooarchaeology

Zooarchaeologists aspiring to social inferences from archaeofaunas have a good toolkit of methods and some conceptual tools that have been established to produce well-supported results in pioneering studies. Much of what I have listed is not new, nor is this an exhaustive list, but I have found this to be a productive way to approach the often daunting project of learning more about the people who acquired the animals, processed them for food and useful products, and discarded their remains in the places they lived. Some conceptual or practical tools mesh together better than others, but, as I said in Chap. 1, this does not mean that one is necessarily wrong and another right. Rather, it may be informative to explore the tensions between them when working through one's data. Finally, the cases cited in this chapter indicate that such endeavors optimally juxtapose archaeofaunal data with that drawn from artifacts, architecture, site structure, documentary sources, and other contextual evidence, truly being cases where "bones are not enough."

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Chapter 26
Doing Zooarchaeology Today and Tomorrow

Zooarchaeology is at an interesting juncture in its history. Archaeological faunal analysts have made great advances in method and practice over the last five decades, and intense debates continue on emergent topics. Much of this progress has depended upon tapping various kinds of knowledge derived from the contemporary world, from the biomedical literature to experiments to ethnoarchaeology and landscape taphonomy. Controversies over the meaning of long bone fracture outlines have subsided as bone structure and the mechanics of stress in bone as a material were understood. Debates over the respective roles of human selectivity versus bone mineral density in determining archaeofaunal element frequencies generated technologically aided techniques for calibrating the key variables of each, and methods for assessing the probabilities of one or the other influence as the dominant process. Intensive actualistic research has identified specific actors' effects on bone, thereby narrowing the range of possible processes, effectors, and actors involved in multiagent accumulations. At some levels, the field has progressed toward greater knowledge.

26.1 Ongoing Issues in Zooarchaeological Inference

Some challenges abide, and new ones face us. As was the case with the biological sciences, zooarchaeologists initially sought to achieve reductionist explanations, emulating the classic example of the physical sciences, searching for few key process that account for the evidence under study, then stipulating simple determinative relationships between that evidence and a causal process. For zooarchaeology, as in some basic forms of biological research this works reasonably well, that is, at the level of what this book calls the action of causal processes, effectors, and actors. Even with these process-product relations, the clearest results may be produced by multivariate analysis, as appears to be the case with distinguishing trample marks from cut marks.

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The problem comes when trying to use these same straightforward procedures to use patterning in the archaeofaunal evidence to make broader inferences about human behavior in its social and ecological contexts. Some zooarchaeologists have been slow to shift from hoping for one or two lines of evidence, or a "magic number," will stand as a proxy for the complex operation of past human behaviors and adaptations. This book has made the case (Chap. 3, Sect. 3.5) that, for such targets of zooarchaeological analysis, considerable actualistically-derived evidence suggests that causation is probabilistic rather than determinative. In these cases, analogical inferences, while not so weak as formal analogies, individually lack the power of single-cause, determinative ones, and so do parallel cases in biological sciences. Yet, as Lyman and I both suggested many years ago, researchers can combine many such analogical inferences to gain some sense of the most probable circumstances that generated a set of evidence we have collected. In other words, the more interesting the question in zooarchaeology, the less likely it is that there will be a "magic number."

I do not advocate stepping back from rigorous scientific methods. Predictive models drawn from behavioral ecology have proved very fruitful in human ecology and some archaeological cases, with predictions phrased and assessed probabilistically. Instead, I simply urge zooarchaeologists to take seriously that we may be at a transition point from the process-product forms of inference that produced such progress in our field over the last 50 years and entering a zone currently being explored by biologists and paleontologists. This level of inquiry will call for analyses that use multiple, independent, and actualistically supported lines of evidence from archaeofaunas and their contexts, as well as judicious application of strong bodies of theory drawn from living biological systems (synecology, behavioral ecology, etc.). Mayr (1982) presented instances of complex inference in the biological sciences. Paleobiologists cited in Chap. 17 are tacking between contemporary landscape data and exploring paleontological data with multivariate methods. Wylie (1989) and Stahl (2002) have explored some of the "behind the scenes" inferential operations involved in archaeology. I suspect that many examples of what most would call "good archaeology," involve such complex analytical work with datasets, even when researchers don't stress the philosophical underpinnings of what they do, nor apply fancy multivariate analyses. Zooarchaeologists are dealing with outcomes of complex systems and seek to work with materials left them by time and taphonomy in ways that acknowledge the nature of the determinative "source side" processes (Wylie 1985). To address these issues, our analytic methods and models should probably be equally multivariate and complex.

One major question to consider is that of the scale of time over which archaeofaunal samples accumulated, and to match appropriate questions to these scalar levels, as do paleobiologists. Clearly if you know the date that Monticello was established as a plantation production system and the year that Jefferson died and most of his property, including its enslaved people, were sold to clear his debts, you can ask human-scale, even generation-scale, questions of the archaeofaunal sample. But if a paleontologist tells you the sample's resolution is around 150 years at best (Terry 2008), are the questions the same? What if your geoarchaeologist colleague tells you the best resolution of scale in a small Pliocene site is 2000 years (Stern 2008), what are the appropriate questions? Scale might be the first questions to be answered on a checklist for the next generation of zooarchaeologists. While this speculation may seem irrelevant to many working with Holocene foragers and pastoralists, when locales are repeatedly occupied, the interaction of time-averaging and archaeofaunal accumulation – sampling scale – should be considered. Those of us working in the last few score millennia have the luxury of being able to bracket site materials with radiocarbon and other dating methods, providing some of that resolution.

26.2 New Methods, Practical Continuities

New technological developments and opportunities for applying zooarchaeological knowledge call for a reordering of priorities and practices in zooarchaeology, at least among researchers investigating diet, domestication, and ancient biogeography and synecology. However, rather than replacing zooarchaeology, stable isotope, zooMS, and genomic research augment it. These can enable zooarchaeologists to pursue topics that focus more on human ecology and social relations. However, even if one aspires to isotopic or ancient DNA analysis, one has to know how to identify specimens to analyze – or work with someone who can. I learned this lesson in working on bone stable isotopes and ancient DNA, when these methods called the taxonomic identifications into question. In one case, two “coyote” specimens had isotopic values that fell into the range of sea otters: a check of the specimens revealed that they were marginally identifiable fragments that could just as readily sort with *Enhydra* and should never have been included in the sample drawn (the case for zooMS!). When selecting *Callorhinus* specimens from the Moss Landing Hill site collection for aDNA analysis, amidst the many unequivocally female and young-of-the-year I sent what I thought were a few rare male specimens, only to learn that they were male California sea lions. These humbling experiences prove that there is no substitute for accurate taxonomic identification based on osteological markers – and that one should be conservative with fragmentary specimens.

I would venture one generalization that applies nearly universally to zooarchaeology: sophisticated quantitative analyses such as Terry’s (e.g. 2007, 2008) work with micromammals can be done, as she states, only because of the detailed data collection, documentation, and publication by an entire generation of researchers. Morin et al. (2016) stress that their relatively high levels of inter-analyst agreement resulted from months of dogged work by each volunteer. There may scarcely be a zooarchaeology lab in the world where afternoon conversation has not turned to that fantasy machine, with its little conveyer belt carrying individual specimens in for instant 3-D outline scanning for overlap assessment and osteometrics, then on to the instant zooMS platform for a quick read on taxonomy, printing the data code card, automatic bagging, etc. But in the meantime, after the tea or coffee break, we have our work before us. Table 26.1 points to at least some of the considerations zooarchaeologists should take into account when approaching their analyses.

Table 26.1 Zooarchaeological analysis in several challenging steps, relevant chapters in text are given in parentheses

I. Think
A. What do you want to investigate?
1. Subsistence (a) *Predation on wild species* (b) *Herd management* (c) *Role of domesticates in farming systems* (d) *Urban supply chains for animal foods* (e) *Non-archaeofaunal resources required to distinguish these*
2. Household food supply (a) *Butchery/selective transport (if applicable)* (b) *Culinary processing modes, energetics* (c) *Modes of disposal* (d) *Non-archaeofaunal resources required to distinguish these*
3. Inter-household sharing or lack thereof (a) *Intrasite activity areas* (b) *Carcass refitting* (c) *Taxonomic differences among houses* (d) *Feasting vs. everyday consumption patterns of modification, discard* (e) *Non-archaeofaunal resources required to distinguish these*
4. Differential animal acquisition, processing, or consumption (a) *As diacritical markers of gender* (b) *As diacritical markers of rank* (c) *As diacritical markers of class* (d) *Non-archaeofaunal resources required to distinguish the above*
5. Long-term site function history
6. Diachronic, regional-scale changes in any of above
7. Animal biogeography and evolution (a) *Climate change effects* (b) *Invasive species* (c) *Non-archaeofaunal resources required to document these*
II. What is the nature of your sample or samples?
A. Stratified site, single component?
B. Excavation by arbitrary or lithologic levels?
C. Was some archaeofauna recovered according to features?
D. When was your sample recovered?
E. Faunal recovery practices at time of excavation? 1. Screened or not screened 2. If screened, what was mesh size - effects on taxonomic representation? 3. Are there column samples, flotation samples? 4. Total sample of site/level, partial sample - how much? 5. Effects of curation practices on archaeofaunal sample
F. How will any of the above affect the composition of the archaeofaunal sample?
G. Given your knowledge of such biases, what classes of data do you deem most relevant to collect?

(continued)

Table 26.1 (continued)

H. How accessible to future researchers will this collection be in the future? Will it be in jeopardy of neglect or destruction? (Chap. 8) 1. If so, can you collect more data than relevant to your immediate research, post in digital repository?
III. Preliminary choice of relevant quantitative units NISP, MNI, MNE, NDE, butchery units, etc. (Chaps. 10, 18, 20, 21, and 22)
A. Given your knowledge of recovery biases and the data you wish to collect, what are the most prudent and effective measures of abundance?
B. How do your methods for recording portion of elements represented affect your options for estimating derived measures of abundance? (Chap. 10) 1. Will you use fractional, overlap, or landmark methods to estimate this?
C. Which options preserve the most flexibility for shifting measures on the basis of what you learn during analysis? 1. e.g. Extreme fragmentation of specific taxa or body segments
IV. How and where will you archive your data for others to check and use in further research?
A. Consult digital repositories e.g. ADS (U.K.), Open Context, tDAR, other institutional systems regarding: 1. Formats required or advised 2. Embargo terms 3. Fee structure
B. Choose a repository 1. Will this affect your data collection methods? How?
V. Primary data collection
A. Select methods for recording data (Chap. 8) 1. Does the physical repository have standard required formats? 2. Will you keep a data tag or card with the specimens? 3. In what form (hand-lettered field form, printed label, barcode, QR)
B. What format will you use for data recording and structuring? 1. Database type (e.g. flat vs. relational, etc.) 2. Database format 3. How do the above choices affect the accessibility to your findings by other researchers?
C. How do your decisions affect comparability with other researchers' data?
VI. Sorting, identification, and attribute recording (Chaps. 8 and 9)
A. Will sorts be done by only you, or by a group under your supervision 1. How will you use persons of different levels of expertise? 2. How will you check output of different sorters?
B. Initial sort into differing levels of identifiability 1. Sort quickly, with minimal reference to comparative samples 2. Keep alert for distinctive features to follow up later
C. Secondary sorts and definitive identifications 1. Determine/record attributes 2. Consider metrical data pertinent to research questions, record 3. How will you report your identifications of rarer taxa

(continued)

Table 26.1 (continued)

- D. Sample extraction for any other pertinent data, e.g.:
  1. Tooth sectioning
  2. Annular growth sectioning fish otoliths
  3. Stable isotopic analysis of teeth or otoliths
  4. aDNA
  5. zooMS
- E. Keep a log of your day-to-day analytic decisions that affect data recorded, digital data fields, variables, etc.

VII. Data structuring and exploration

- A. Taxonomic data
  1. Are recovery methods likely to have affected taxonomic representation? (Chap. 8)
  2. If analyzing a subsample of a larger assemblage, how have you established that your sample is representative of the larger aggregate?
     - (a) *e.g. Sampling to redundancy, etc. tactics* (Chap. 22)
  3. How will you report and document unique species or interspecific differences (Chap. 9)
- B. Element and portion frequencies – within and between taxa. (Chaps. 18, 20, and 21)
  1. Does exploration of frequencies (e.g. histograms, x-y plots, simple statistical tests etc.) reveal strong biases away from original representation of elements in the body?
  2. Do these correlate with bone mineral density indices?
  3. Do these correlate with nutritional utility indices?
  4. What factors may have created this structure in your data (selective transport, in situ destruction by humans, carnivores, etc.)?
  5. Consult data on modification attributes, site context, sedimentology.
- C. Modification attributes (Chaps. 11, 12, 13, 14, 15, 16, and 17)
  1. Does the site's geological/geomorphic context relate to occurrence of attributes, e.g.:
     - (a) *Relation of sedimentary matrix to abrasion through geologic action, trampling,*
     - (b) *Does geomorphology suggest locality was good carnivore lair site, etc.)?*
  2. How do cut, chop, and scrape marks reflect processing behaviors?
  3. How do patterns of thermal alteration reflect processing and/or disposal behaviors, site formation?
  4. How do fracture patterns reflect processing behaviors, nonhuman modifications, site formation processes?
  5. Knowing what you now do about assemblage composition, will refits of broken bones or carcass refitting repay the time, in terms of information relevant to questions you propose to investigate?
  6. How do traces of carnivore, rodent, root, etc. modification reflect site formation?
  7. How do patterns of weathering and or other geological forms of bone modification reflect site formation?
     - (a) *Span of time over which bone accumulated*
     - (b) *Degree of impact of the processes on small/delicate bones, etc.?*
- D. How may the above patterns of representation and modification affect analyses based on element frequencies (e.g. age profiles derived from dentitions of different-sized animals vs. selective transport, interspecific variations in NISP, etc.)?
  1. Are there other exploratory methods you can use to narrow or define these possibilities?
  2. Note how you will discuss this in your write-up in your log
- E. Double-check whether any of the patterning in your data might depend upon the quantitative units used or methods of aggregation (Chap. 18)

VIII. Go back to your original research questions and goals: think again

(continued)

Table 26.1 (continued)

A. Which issues of those you originally defined can you defensibly address, given what you now know about the nature of the assemblage? 1. What arguments can you make to link significant patterns in your data with the past processes you set out to investigate
B. Are there other topics and questions that analysis of the archaeofaunal data suggest to you at this point?
IX. Report your findings
A. Select the appropriate outlet(s) for your results, according to topics, theory, and methods mobilized in your research
B. Strive to be intelligible, despite all the specialized jargon 1. Select and produce appropriate tables, charts, illustrations to support your arguments and inferences, given outlet type and standards
C. Chose a way to present as much of your basic data as possible, so that others can evaluate your inferences and use your data for comparative purposes 1. How much and what data will be included as in-text tables, appendices 2. How much can be included as digital supplemental materials in your target journal or monographic series? 3. How much will you place in accessible form in a digital repository as soon as possible?
D. Send your draft to your most critical zooarchaeological colleague 1. Revise per colleague's suggestions
E. Ask an archaeological colleague who is *not* a zooarchaeologist to read your revision and suggest changes for broader circulation 1. Revise again, as needed
F. Submit your revision 1. Revise per reviewer comments
X. Prepare your base data for upload to your selected digital repository, as needed
XI. Take a well deserved break.

Many years ago, Grayson (1981) stressed that explicit and detailed documentation of archaeofaunal materials underlies all advanced analyses. This is not intended to discourage, but rather to encourage, the painstaking labor involved in basic research in zooarchaeology. It pays off, it not in your own hands, then in those of others. Several stable repositories for digital archaeological data are available today. I am preparing my own archaeofaunal data with documentation for deposit at one of these, with the hope that others can work with them productively.

26.3 Conclusion

Recalling my graduate student days at UC Berkeley, when my professors encouraged me to take up "archaeological faunal analysis," I am deeply impressed by the amount of knowledge that a few visionary notions – and a staggering amount of hard, tedious work by many researchers all over the world – have produced since then. However, writing this book has also brought me back to what David Clarke

(1973) called "critical self-consciousness," that tipping point from the self-congratulatory, "Look how much we know," to the realistic and humbling recognition of, "Look how much we don't know." But rather than letting this be a cause for despondency, I trust that, "how much we don't know" presents a challenge to push a little further into clarifying ambiguities and reducing our ignorance.

I encourage zooarchaeologists to slog through some morass of ambiguity in archaeofaunal interpretation, rather than going for a virtually impregnable case study on a banal topic to publish in a flagship journal – what Lewis Binford (personal communication, 1979) once called, "twirling and pirouetting." Our narratives, the stories about the human past we tell from our data, must be scientific, not in the sense of appealing to some sacred body of theory but in the sense of being explicit about one's methods and systematic in the pursuit of clarity (Lyman 2008). A casual perusal of *Science* or *Nature* shows that articles in other disciplines often devote 50% of page space to detailing materials and methods. Some zooarchaeological articles follow this model, but a distressing number of ostensibly data-grounded zooarchaeological pieces do not disclose what was deemed unidentifiable, how or why counting units were chosen, or other salient methodological details. It's not science if you can't replicate the exercise.

We are now have the third generational cohort of zooarchaeological researchers entering the field and are seeing how their work builds upon – if only to challenge – those of the founding generation and their students. As one of that first cohort, I stated at the beginning of this book that my best wish was not that it be a definitive, final statement on zooarchaeology, but rather that it offer a framework for arranging and mobilizing the constant stream of new information in this lively and growing field. I also said that I hoped to assemble, as well as I could, a kind of methodological and conceptual toolkit for getting on with zooarchaeological research. It is with those intentions that I have written it, and I hope that this will be useful to my colleagues, present, and future.

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