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,

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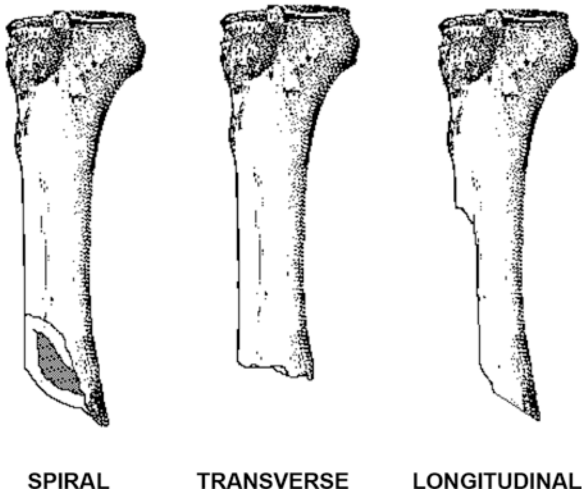

Fig. 11.1 Diagrammatic representation of spiral, transverse, and longitudinal fractures on a ruminant radius. The spiral fracture shows the winding of the break around the shaft of the bone. (Illustration by the author)

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.

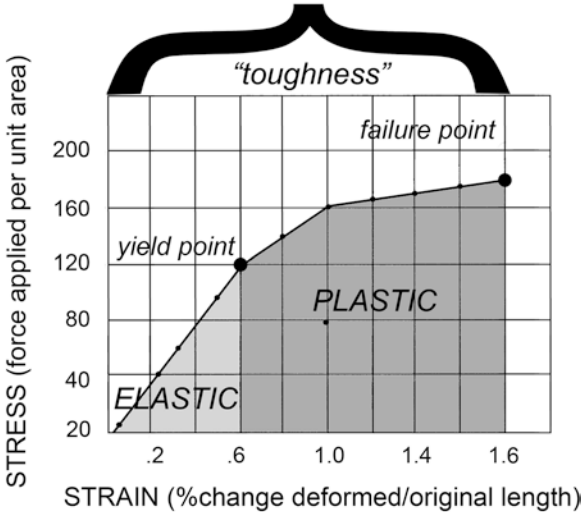

Fig. 11.2 Graph showing zones of elastic and plastic deformation, with the yield and failure points, of a body of a hypothetical deformable material. (Figure by author)

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.

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

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"

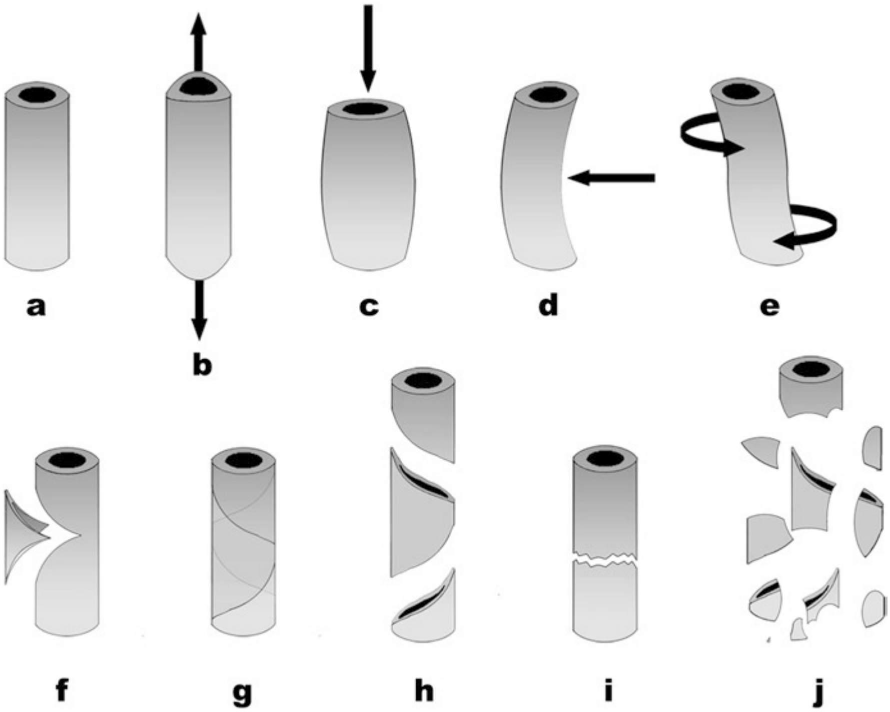

Fig. 11.3 Diagrammatic representation of stress and strain on bone cylinders and possible outcomes. (**a**) A hollow cylinder of bone in unstressed state. (**b**) The cylinder deforming under vertical tension. (**c**) The cylinder deforming under vertical compression. (**d**) The cylinder deforming under 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.

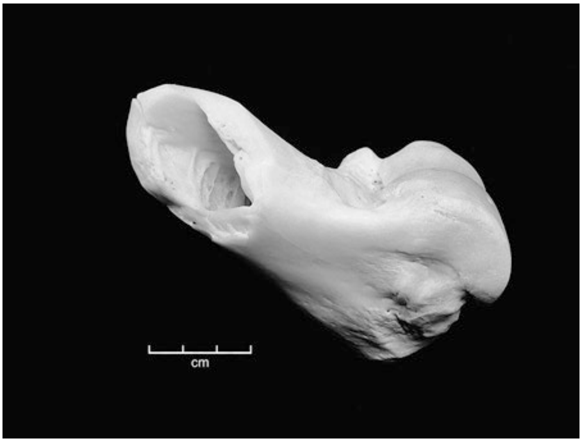

Fig. 11.4 A distal cow humerus, showing a spiral fracture on fresh bone. The break terminates as the break surface winds around the bone and the point at which the perpetuating crack of the force front meets the initial crack. Arrow shows termination point (Photo by Don Harris of experimentally broken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

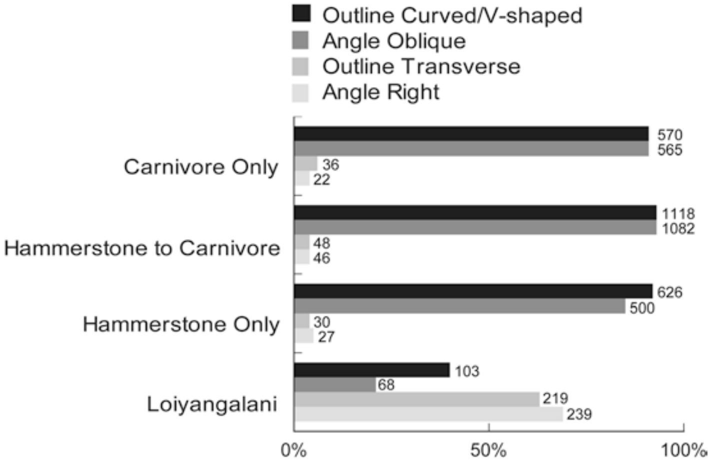

Fig. 11.8 Graphic by Thompson (2005: 85, Fig. 11), showing Marean et al. (2000) fracture outline and angle data for carnivore only, hammerstone only, and hammerstone-to-carnivore experimental breakage of fresh long bones. The lowest register presents Thompson's data from specimens recovered from the 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*)

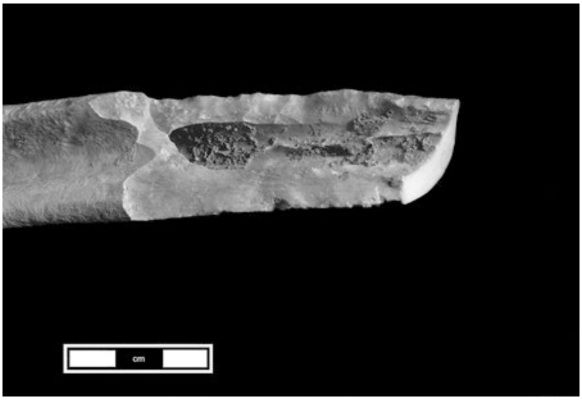

Fig. 11.9 Post-mineralization break across a fossilized deer metatarsal from Pliocene paleontological deposits in the Nihewan, western Hebei Province, Peoples Republic of China. Note the flat break surface and its different color from the rest of the older, undulating break surface, which shows hackle 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

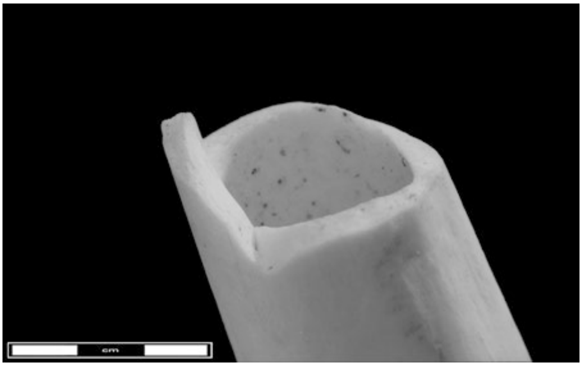

Fig. 11.10 Caprine (sheep/goat) femur shaft from Site 105, a modern pastoralist encampment near Koobi Fora, East Lake Turkana, Kenya, showing near-transverse fracture across shaft, with evidence for thermal stress on break surface (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September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

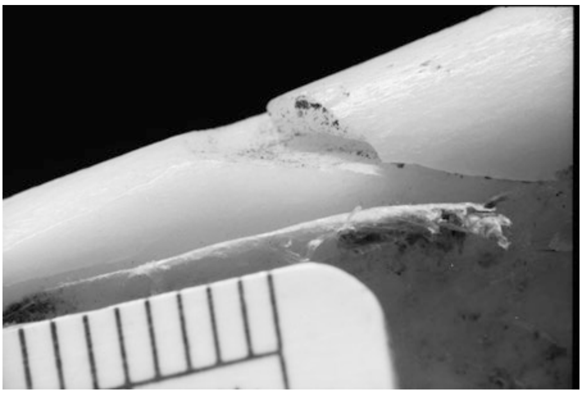

Fig. 11.11 Chop mark on diaphysis, showing the *panga* chop mark and the line of the fracture surface running on from where this terminates. Scale: lines are millimeters (Photo by Don Harris, specimen collected by D. Gifford-Gonzalez in September 1973)

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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