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Determination of the Pretreatment of Bone: A Macroscopic and Microscopic Approach to Fracture Patterns

Theresa Jo Woltanski
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Theresa Jo Woltanski entitled "Determination of the Pretreatment of Bone: A Macroscopic and Microscopic Approach to Fracture Patterns." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Anthropology.

William M. Bass, Major Professor

We have read this thesis and recommend its acceptance:

Walter E. Klippel, Charles H. Faulkner, Lyle W. Konigsberg

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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DETERMINATION OF THE PRETREATMENT OF BONE: A MACROSCOPIC AND MICROSCOPIC APPROACH TO FRACTURE PATTERNS

A Thesis
Presented for the
Master of Arts
Degree
The University of Tennessee, Knoxville

Theresa Jo Woltanski
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ABSTRACT

Actualistic studies of bone can contribute to an understanding of cultural modification of archaeologically recovered bone. Two such cultural modifications include cooking and subsequent fracturing during food preparation. In an effort to understand the fracture dynamics and patterns of cooked bone, a three part study is undertaken including fresh, boiled, and roasted bone. This study incorporates mechanical stress testing of bone, hand-fracturing with study of macroscopic fracture details, and examination of surface morphology using a scanning electron microscope (SEM).

Results of this study indicate that macroscopic features such as texture, fracture class, impact point, presence of longitudinal fractures, and fractures that continue through the diaphyseal ends are not independent of pretreatment and should be noted during analysis. Changes in microscopic surface texture and the ability to view associated structures form a possible basis for the assignment of bone to its treatment class. Mechanical testing indicates that boiled and fresh bone can carry similar loads to first failure, although the degree of failure is more complete for fresh bone. The strength of boiled bone declines significantly with cooling. Roasted bone is significantly weaker than the other two groups.

This study may be applied to faunal assemblages and in some cases, physical anthropology. Prior to the advancement of a method to determine the treatment class of bone, however, post-depositional and diagenetic factors must be taken into account.

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CHAPTER 1

AN INTRODUCTION

Bone was one material commonly selected for cultural modification by early humans. This modification was not only in order to maufacture makeshift tools out of a readily available substance (Sadek-Kooros 1972), but also to better remove necessary nutrients from the bone in the form of marrow or grease (Binford 1978). Calcified tissue has consistently continued to undergo various modes of modification by humans, whether for ornamentation or food. As a result, fragmented and fractured bone in the archaeological record is a common occurrence. But bone is modified by sources other than humans, including carnivores, trampling, and geologic forces (Morlan 1983). In recognition of this problem, bone has been studied in an effort to differentiate hominid/human-modification from other sources and, beyond that, to make cultural inferences based on that modification.

Among those who seek to make cultural inferences from artifactual remains are zooarchaeologists, who identify and analyze faunal remains. Although initially an area of study for zoologists or paleontologists, zooarchaeology has become a specialized discipline in its own right in the past 20 years (Robison 1987). Robison (1987) has divided zooarchaeological literature into three phases. The first he labels the Formative Period, the second the Systematization Period, and the third the Integration Period.

The first period was a time of development and experimentation. Few early reports were published and animal bone was largely ignored (Robison 1987). In contrast, the second period showed an increased interest by archaeologists in the field, with faunal analyses appearing in site reports, albeit as appendices, or as separate reports altogether. The Integration Period was part of the new archaeology. Within this period in zooarchaeology, integrated faunal analyses and interpretations have been made, with a greater emphasis on determining subsistence patterns. Increased theoretical and methodological literature appears, with a recent growth in taphonomic studies (Robison 1987).

The literature of bone modification to be discussed in the following pages is an outgrowth of this period of integration. Realizing the amount of knowledge available from faunal assemblages, archaeologists have conducted actualistic studies and utilized ethnographic observations in order to more fully interpret skeletal remains. Physical anthropologists have also taken full notice of the advantage of taphonomic studies, utilizing existing data as well as conducting their own studies in order to better interpret post-mortem alterations present on human skeletal material, including archaeological populations and more recent material.

THE EARLIEST HOMINID MODIFIED BONES

One raging anthropological debate revolves around the search for the earliest hominid modified bones, and, in conjunction, the

behavior of these early hominids. Dart (1959) proclaims that the earliest bones modified by hominids can be found at the South African sites of Taung, Sterkfontein, and Makapansgat. Here Dart claims the australopithecines had used bone, tooth, and horn for their tools, creating assemblages of skeletal remains for the purposes of their "Osteodontokeratic" culture. Later authors (Brain 1981; Sutcliffe 1970) dispute the claims of authenticity for these implements, proclaiming them psuedo-tools caused by weathering, abrasion, trampling, and accumulated by hyenas.

Other early sites included in the search for hominid-modified bone are located at Olduvai Gorge, Tanzania, and Koobi Fora, Kenya. Faunal remains are found, some in association with lithic artifacts. Cutmarks are identified on some fossils from these sites and marrow-processing activities are suggested as early as 1.75 million years ago (Bunn 1981; Potts and Shipman 1981). Debate has raged concerning the activity represented by these cutmarks. Bunn and Kroll (1986) feel these marks represent meat removal; other suspected activities include removal of the periosteum prior to fracture of the bone for marrow (Binford 1981), or skinning (Shipman 1984). The possible niche filled by early hominids (i.e. hunting, scavenging or both (Shipman 1984)), is also a matter of controversy, as well as what sort of site these assemblages may represent (i.e. home base, or a butchery site (Potts 1984)).

During the inspection of these cutmarks and fractures, several actualistic studies were undertaken in order to more positively characterize these marks as having been caused by hominids. Potts

and Shipman (1981), with the scanning electron microscope (SEM) as a diagnostic tool, compare the marks on fossil bones with marks made on modern specimens by known implements and causes. These latter marks include carnivore tooth scratches, rodent gnawing, root etching, and sedimentary abrasion. Bunn (1989) looks at various bone fracture patterns by both humans and carnivores in order to compare the known specimens with the fossil specimens.

BONE MODIFICATION STUDIES

The search for the earliest hominid modified bones is only one example of a high-profile current debate. Other disputes involving the interpretation of modified bone exist.

Considering the many and varied circumstances under which bone is examined, the number of specific bone modification studies by anthropologists is small. This number includes both analyses of archaeological assemblages and actualistic studies. A greater number of studies have been conducted in the biomechanical field and are discussed in Chapter Three.

The differences between human-modified and carnivore-modified bone is one area of observation. Bonnichsen (1973) collects bones from the animal cages at the Alberta Game Farm and details what he feels is a consistent pattern of modification, including tooth perforation marks, gnawing, splintering, a scooped-out appearance, and spiral fractures directed from the epiphyseal ends. In addition, he conducts experimental controlled breakage studies (1973, 1979)

both on glass tubes and bovid bones as well as with mineralized specimens from the National Museums of Canada. His work contains detailed discriptions; and he feels the presence of an impact site as well as spiral fractures radiating from the midshaft are most characteristic of human modification. This work is summarized by Morlan (1983). Later studies (Woltanski 1990) suggest, however, that an impact site is not always present and differing breakage strategies result in differently patterned spiral fractures (Binford 1981).

Other carnivore modification studies include an analysis of bone damage caused by hyenas (Hill 1989) and a study by Kent (1984) observing meat removal by domestic dogs from boiled and broiled bones. A more recent study (Willey and Snyder 1989) examines canid scavenging in order to address implications for time-since-death observations in the medicolegal field.

Modification to human bone by carnivores is also described (Haglund et al: 1988). In concert with those marks mentioned by Bonnichsen (1973), scoring or linear marking of bones is also noted. The identifying characteristics of rodent gnaw marks are also described (Haglund et al. 1988). These marks are contrasted with the appearances of cutmarks caused by a variety of instruments in a study by Potts and Shipman (1981).

Natural phenomena are another source of bone modification. Various studies examine the changes in bone that occur due to natural causes. Both Agenbroad (1989) and Oliver (1989) document bone damages previously thought to be caused only by humans, such as spiral fracture and polish on the break, that have been caused by

natural taphonomic agents. These include biological agents such as trampling, hydrological and geological forces, and mechanical agents like boulder fall (Agenbroad 1989). Haynes (1983) describes spiral fractures due to carnivore activity and trampling. An earlier study (Miller 1975) also examines natural phenomena that could be mistaken for human activity. These include weathering cracks, fractures, and splinters. Weathering is a geological phenomena associated with bone change (Davis 1985). Behrensmeyer (1978) presents a sequence of six stages of weathering ranging from no weathering (0) to destruction of the bone (5). Another study (Tappen 1969) finds the placement of weathering cracks corresponds with split-lines (lines artificially induced for the study of the surface organization of compact bone).

Hare (1980) studies the chemical and physical alterations occurring in postmortem bone samples prior to destruction or fossilization. Part of this diagenetic study is conducted in the laboratory, with Hare heating bone samples in various amounts of water. Depending on the presence and amount of water, leaching of amino acids and peptides from protein breakdown varies greatly. Eventually, collagen also leaches out. The strength and hardness of the bone studied decreases depending on the length of time the reaction is allowed.

Fewer studies are undertaken in order to further elucidate characteristics within the category of human modification, however. In additon to the experimental work by Bonnichsen (1973, 1979) addressed above, some experimental work by Sadek-Kooros (1972,

1975) attempts to reproduce breaks seen in an archaeological assemblage. Davis (1985) investigates fracture location, orientation, and morphology in order to observe the effects of bone size, choice of skeletal element, and degree of weathering. Bones are broken using stress machinery and results are applied to South African faunal assemblages. In addition, Zierhut (1967) relates the methods of bone breakage employed by the Cree Indians of Calling Lake in Alberta, Canada while Lyman (1978) discusses pattern recognition in the archaeological record.

Noe-Nygaard (1977) also discusses pattern recognition in bone assemblages. The bones from four Mesolithic sites are examined in order to illustrate the role of man as a taphonomic agent. Multiple similarities are noted in marrow fracturing techniques between the older sites on one hand, Star Carr and Kongemosen, and the younger two on the other, Praestelyngen and Muldbjerg. Differences in the number of fragments are seen depending on the technique used even though skeletal element remains constant. Noe-Nygaard suggests that the various types of marrow fracturing seen can be associated with level of technological development. She then concludes that bones fractured at the earlier, aceramic sites were broken prior to cooking while those broken at the later, ceramic sites were subjected to boiling prior to breakage.

Newcomer (1974) describes bone tools from Lebanon, and attempts to manufacture some himself. Bone tool descriptions from other localities include those from the Lubbock Lake site and the Bonfire Shelter (Johnson 1982). Yesner and Bonnichsen (1979) report

on a strategy to produce bone splinters similar to ones found at the Paxson Lake site in central Alaska.

One item consistently mentioned is the fact that bone may have been subjected to pretreatment such as boiling, roasting or soaking prior to modification. For instance, Bonnichsen and Will (1980) discuss pretreatment of animal bone and antler, such as soaking in water or urine, in order to soften the substance before working. An earlier study (Clark and Thompson 1953) states that soaking antler in water softens the material and makes it easier to groove. Newcomer (1974) mentions that among the raw materials he attempts to work with are cooked bone and water-soaked antler. Semenov (1964) states that bone soaked in water is easier to work with flint tools and mentions that contemporary Russian peasants steam bone prior to working it. He feels that Paleolithic peoples may have soaked the bone and then placed it in the fire to warm it. Gifford-Gonzalez (1989a), while analyzing broken animal bones from a Dassanetch site near Lake Turkana, questions the effect of boiling and roasting prior to breakage on fracture patterns. Ethnographically, however, marrow breakage is observed both before and after cooking (Yellen 1991).

Several of these authors (e.g. Bonnichsen and Will 1980; Gifford-Gonzalez 1989a) point out that no methods have been developed to determine if pretreatment has taken place while the remainder fail to mention it at all. Binford (1981) states that food preparation can be expected to leave subtle diagnostic traces on the skeleton but adds he does not intend to research the differences. In a

study analyzing the color, morphology, crystalline changes, and shrinkage of burnt bones and teeth using the SEM, Shipman et al. (1984) state that roasting was the most probable method of cooking in the Lower and Middle Pleistocene, but at temperatures far too low to be determined using their method.

Few studies of this research problem have been conducted. In a study similar to that of Shipman et al. (1984), Gilchrist and Mytum (1986) macroscopically examine bones which had been burned in an open-air fire for color and shrinkage. The fires are monitored for maximum temperature. The samples recovered from these fires are then compared with archaeological specimens from Castell Henllys, an Iron Age fort. Based on the similarity of appearance between the former and the latter, the authors suggest bone at this site was heated in an open air fire at some point.

Another study (Horwitz 1987) utilizes a sample of four different cow long bones, numbering fourteen in total, and three separate breakage strategies. Roasted, boiled, and fresh bone are all compared. Horwitz describes each fracture briefly, though any synthesis of the material must be performed by the reader. Thus, results are slightly more difficult to interpret. Although Horwitz concludes that "several differences seem, in fact, to be related to the microstructural changes resulting from cooking" (1987:6), she never enumerates these differences. She seems to be hampered by the small sample size and lack of continuity both between element type and breakage technique. Horwitz concludes with a warning that patterns observed for cooked bones may apply to dry bone in one form or

another.

An investigation by Black (1989) examines the effects of cooking heat on bovine bone. Four bones are utilized for a control group, with fourteen other bones boiled and seven roasted. Only a small portion of the bones are fractured by hand; the remainder are sawed into segments. Sections of the fractured surfaces of these bones are examined under the light and scanning electron microscope. Promising differences are seen in the morphology of the fractured surface using SEM. Fresh bone displays a cleaner break while roasted bone shows a more jagged surface. Due to the very small sample used, no method is presented for identifying the various groups of bone.

Fifty pig femora are the basis for another study (Woltanski 1990), although only comparisons between boiled and fresh bones are made. Two breakage techniques are used. Several differences are noted, both between the state of the bone as well as the breakage technique. Boiled bone generally displays more fragments, more hinging or stepping of the fracture, and fracture lines that split the diaphyseal plate. Also, boiled bone in this study always breaks with a spiral fracture and has a rougher fracture surface texture. Fresh bone exhibits some oblique fractures, and has a smoother texture. Fracture lines that run through the diaphyseal plate are only present with one breakage technique and only rarely. Impact sites are not always clear. Although with a larger sample than Horwitz, the study stops short following macroscopic analysis and needs a redefinition of fracture types, such as spiral and oblique.

Lastly, William Whitehead (personal communication 1992) studies the direct stress required to fracture cooked and fresh bone using an Instron stress testing machine. It is found that immediately following cooking, bone can undergo much more stress prior to fracture. This amounts to nearly 20,000 pounds/in.^{2} for boiled bone. This strength decreases proportionally with the amount of time following boiling. Unboiled bone's strength did not fall so precipitously. This is consistent with the findings of both Horwitz (1987) and Woltanski (1990), who, although fracturing by hand, note that boiled bone seems more difficult to break. In a related study, Nicholson (1992) suggests that cooking may detrimentally affect a bone's chances for survival in the archaeological record if it is not buried.

THE CURRENT STATE OF BONE RESEARCH IN ANTHROPOLOGY

It should be noted that among those doing research on archaeological bone in anthropology there is not always agreement of opinion, interpretation, and data. For instance, in one edited volume, Bunn (1989) includes numerous bone flakes and extensive fragmentation as characteristics of human-manufactured assemblages, not those of carnivores. In the very same volume, Hill (1989) credits a high degree of fragmentation, spiral fractures, and bone flakes to an assemblage created by the modern hyena. Another example of the diversity of opinions is reflected in Binford's (1981)

rather cutting viewpoint of Bonnichsen's (1973) choice to utilize only one fracture technique in his experimentation.

An overview of current knowledge about bone technology was recently written by Johnson (1985). This review was written to disperse information about bone research in an attempt to lessen some of the polarized disagreements that have resulted from these differing ideas. This work represents a great amount of research and, to a certain degree, succeeds. However, she also adds her own fuel to the fire. For example, in one paragraph, Johnson states that fracture patterns and the response of bone begins in the microstructure. Four paragraphs later she writes that fracture fragmentation is governed by the tubular nature of the material. This tube shape is a characteristic on the macrolevel. She takes a number of researchers to task for failing to correctly identify a spiral fracture as opposed to "horizontal tension failure" (Johnson 1985:172) which she describes as the fracture response of dried bone. However, her definitions of the two overlap to a certain extent, in that a spiral fracture is a break inclined at a 45° angle while a horizontal tension failure can be a diagonal break. There is no mention of how to tell the difference other than the former is the response of a fresh bone while the latter is that of a dry bone. However, as will be mentioned later, a spiral fracture is not limited in its occurrence to fresh bone. Unfortunately, this review is also due for an update. For instance, some comments about the cement line in bone have since been refuted (Burr et al. 1988).

THE PROPOSED STUDY

The proposed study is an effort to fill a portion of a gap in the current literature dealing with the pretreatment of bone. Fresh bone and bone that is pretreated by either boiling or roasting for an extended period of time will be experimentally broken. It is hypothesized that through analysis of the fracture patterns and surfaces that these differences in the original state of the bone can be determined. The research will be significant in a number of ways.

Bone appears at most archaeological sites and affects all aspects of the archaeological record, including prehistoric and historic sites. This study could increase the cultural inferences made from archaeological bone. Any ability to determine the method of food preparation used by past groups of people will greatly enhance the interpretation of their lifeways.

Human bone that has been modified prior to deposition is also found frequently in the medicolegal field. The services of a forensic anthropologist may be required to determine the age, ethnic background, and sex of a skeleton as well as detail any trauma that may be present. Some individuals may be found with little or no modification to the skeletal material. However, this is not always the case. In the Jeffrey Dahmer incident, one victim was dismembered and the pieces smashed with a sledgehammer prior to their deposition (Miller et al. 1991). Other individuals were allegedly cooked following dismemberment (Prud'homme 1991).

If successful, the proposed research will not only increase the

cultural inferences one can make from the archaeological record, but also add to the knowledge of the predepositional state of bone in the medicolegal field.

This study can be considered middle-range research. Due to the particular form of research that is anthropology, we often attempt to investigate unobservable processes, such as the formation of the archaeological record (Gifford-Gonzalez 1989b). Thus, analogic reasoning and uniformitarian assumptions must be utilized. Binford (1981) feels that in order to accurately change from observations on statics to statements about dynamics, we must designate standards for recognizing "signature patterns" (1981:26) that may be preserved in the archaeological record. A signature pattern must be shown to be redundant and unambiguous in order to set one agent of modification apart from another. Thus experiments must be actively conducted in the present in order to observe patterns generated when there is little problem regarding the identification of the agent responsible for the pattern. Binford makes a call for more middle-range research that is independent of general theory.

CONCLUSION

It has been properly recognized within the last few decades that skeletal material can offer a great amount of information if not relegated to a "laundry list" at the end of a report. To this end, there has been an increase in taphonomic and neotaphonomic, or actualistic, studies. Questions asked of skeletal material include:

when was this material first chosen for modification by hominids, and how can human modification be discerned from other alterations, including those by carnivores and geologic forces? Lastly, can cultural inferences be made from the appearance of bone? The study proposed here initiates a closer look at fractured bone in order to determine its pre-depositional state.

CHAPTER 2

THE STRUCTURE OF BONE

In order to better understand the changes that occur in bone during a modification process such as roasting or boiling, as well as during the fracture process, it is necessary to examine the form and structure of bone. Bone, one of the body's connective tissues, is a living tissue. It is composed of a dense matrix with cells embedded within that matrix (Pritchard 1972a). It composes the skeletal framework for the bodies of the majority of vertebrates (McLean and Urist 1968).

BONE MACROSTRUCTURE

Although several categories exist into which a bone can be placed based on its appearance; including long, flat, or irregular; the bone type that will be most discussed in this work is the long bone. The femur and humerus are typical examples of long bones. The long bone is composed of a shaft, or diaphysis; consisting of a cylinder containing a marrow, or medullary cavity. The ends, or epiphyses, of the bone are separated from the diaphysis by a cartilagenous pad during the developmental years, and later become continuous with the shaft. This pad is called the epiphyseal plate.

Weidenreich (1930 in Pritchard 1972a) initially recognized 5 types of bone based upon the arrangement of their constituents. This

categorization is rather cumbersome to use in practice, however. Thus, in the fully-developed bone, two types of bone structure are identified macroscopically. The first is spongy, or cancellous, bone. This bone is composed of a fine latticework of bone partitions called trabeculae which contain marrow. It is found in the ends of the long bones, the vertebrae, and in most of the flat bones. The second is cortical bone, which is hard and compact. It surrounds the marrow cavities of the long bones.

The two bone types discussed above are considered mature bone. In embryonic development and in the early formation of fracture callus, a third type of bone can be seen (Vaughan 1981). This is woven bone, coarse in appearance with a more random arrangement of microstructure and cells (DeKleer 1982). Some woven bone may persist in the adult at attachment sites of the ligaments and tendons (Vaugan 1981).

McLean and Urist (1968) discuss the two membranes of bone. The first is the periosteum, which surrounds most bones. In the growing individual, this sheath consists of collagenous fibers, fibroblasts, and an inner layer of osteoblasts, cells associated with growing bone. The membrane is an attachment site for tendons and carries blood vessels and nerves in the adult. In the adult, the periosteum can be stimulated to form new bone.

The endosteum, on the other hand, lines the walls of the marrow cavity. It has both osteogenic and hemopoietic qualities and is also stimulated at times of fracture.

MICROSCOPIC STRUCTURE

The actual cellular components of the skeleton are minimal and bone is, for the most part, composed of a mineralized matrix. In compact bone, this matrix is deposited in layers approximately 3-7 micrometers thick (Fawcett 1986). These layers are typically called lamellae, hence the term lamellar bone. Most adult mammalian bone is lamellated. Changes occur between alternate lamellae in the size, occurrence, and direction of bone fibers (Pritchard 1972a).

Throughout the bone substance can be found small cavities called lacunae that house bone cells. Canaliculi, or small fine canals, radiate from the lacunae and are essential to the nutrition of the cells (Fawcett 1986).

In compact bone, the lamellae are arranged one of three ways, either as osteons, interstitial bone, or as circumferential lamellae. The majority form osteons, or haversian sytems. In these systems, the lamellae circle around vascular channels coursing longitudinally within the bone. In cross-section, osteons can be seen as cylindrical units or concentric rings around an opening (Fawcett 1986). In new bone, these cylinders are known as primary osteons; these eventually erode and fill in. The new cylinders are referred to as secondary osteons. Secondary osteons can be differentiated from those that are primary by their larger size, and their external boundary line of clear cement (Pritchard 1972a). These new generations of osteons cross over older osteons, leaving irregular patches of lamellae. These fragments are termed interstitial bone (McLean and Urist 1968).

Lastly, according to Fawcett (1986), the circumferential lamellae may be found directly adjacent to both the periosteum and endosteum. These are layers that, without interruption, circle much of the shaft of the bone.

Vascularization of the bone occurs through one of two channels. The haversian canal travels through the center of the osteon. Haversian canals are linked to each other, to the surface, and the marrow cavity by transverse channels called Volkmann's canals. These microscopic structures are represented in Figure 1.

THE CONSTITUENTS OF BONE

There are three basic constituents of bone, including fibers, crystals and cement. The fibers are composed of collagen; densely-packed bundles of these fibers are found throughout bone (Pritchard 1972a). There are 5 types of collagen which differ in their molecular structure, chemical characteristics, and tissue distribution. The type found in bone is generally referred to as Type 1 (Vaughan 1981). Collagen, when viewed with an electron microscope, is made up of fine fibrils with double cross banding at intervals (McLean and Urist 1968). There are numerous variations in the grouping and orientation of the fibers. This variation accounts for the differences in appearance noted between various bone samples. One third of the dry weight of bone is, on average, composed of collagen (Pritchard 1972a).

A second type of fiber, also Type 1 collagen, may be present in

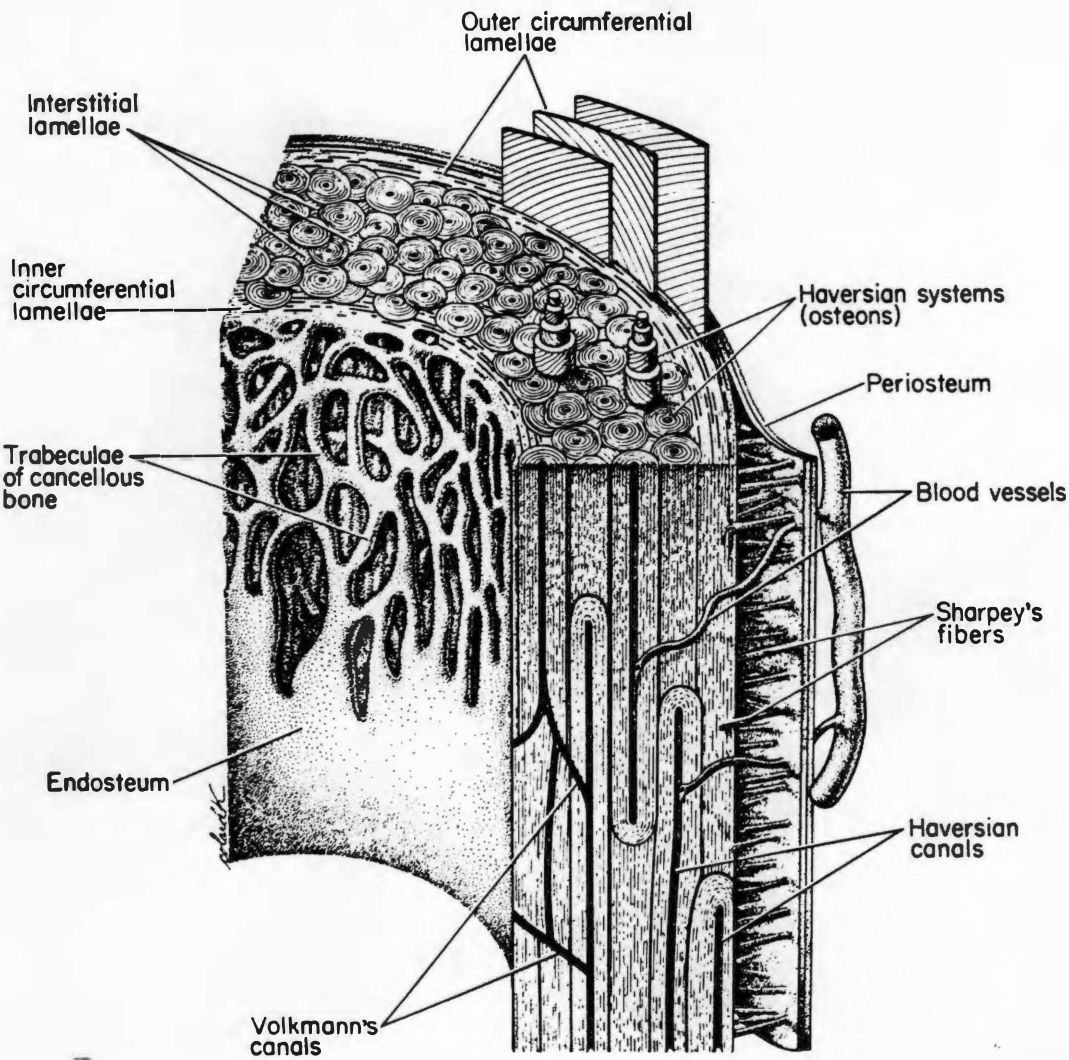

Figure 1: The microscopic structure of bone.
Taken from Fawcett (1986:206).

bone and although not considered a primary component, should be mentioned. These fibers are called Sharpey's fibers, or extrinsic fibers (Boyde 1972). Sharpey's fibers are generally regarded as extra-osseous collagen bundles that have been incorporated into the bone as it develops (Smith 1960). This would include extrinsic tendon or ligament bundles (Boyde 1972) or fibers from the outer layer of periosteum, anchoring the membrane to the bone (Fawcett 1986).

Nearly two-thirds of the dry weight of bone is inorganic and crystalline in nature. These crystals are the second basic constituent of bone (Pritchard 1972a). Currently, the bone crystals are considered either needle-shaped or, quite the opposite, plate-like. The size of these crystals is debated; however, current estimates suggest an average diameter of 50 Angstroms (A) (McLean and Urist 1968), with suggested crystal lengths ranging from several hundred A (Pritchard 1972a) to several thousand A (McLean and Urist 1968). The x-ray diffraction pattern of these crystals is similar to that of the mineral hydroxyapatite (Vaughan 1981), and these crystals are generally referred to as hydroxyapatite. Even so, the crystals should not simply be regarded as being the same as the mineral, as different anions and cations may be associated with the crystal latticework and different chemical and physical bonds may be present. In addition, some part of the calcium and phosphate that is recorded in diffraction studies may be non-crystalline in form (Pritchard 1972a).

Once the fibers and crystals have been removed, the third basic component of bone, cement, remains. In most areas of bone, the fibers are so tightly spaced that the cement is unnoticed, however,

fiber-free cement lines, approximately 1-2 micrometers wide, can be seen with the light microscope in some regions (Pritchard 1972a).

Chemical analysis indicates that the principal ingredients of bone are collagen, calcium, phosphate, and water with significant amounts of mucopolysaccharides, glycoproteins, lipids, carbonate, citrate, sodium, magnesium, and flouride. There appears to be a number of more minor ingredients as well. It can be generalized that the collagen is present in the fibers; the calcium and phosphate in the crystals; and the remainder are present in the cement (Pritchard 1972a). A more recent analysis by Burr et al. (1988) suggests that cement lines are areas of reduced mineralization composed of sulfated mucosubstances.

Pritchard (1972a) feels that the extremely intimate relationship present between the above components; fibers, crystals, and cement; nears an integration on the molecular level. Further evidence is present to suggest there are both chemical and physical bonds between the materials (Pritchard 1972a).

BONE CELLS

Various cells are associated with the bony matrix. These include the osteoblast, osteoclast, and osteocyte. As previously mentioned, the osteoblast is connected with the growing and developing bone. Osteocytes concern themselves with the maintenance of bone tissue while osteoclasts deal with the resorption of bone.

The osteoblast, resting on a bone surface, takes in a number of substances, including amino acids, glucose, and sulfate. It manufactures these into a substance called osteoid, composed of collagen, mucopolysaccharides, and glycoproteins (Pritchard 1972b). After the secretion of osteoid, calcium phosphate crystals are deposited, causing a change to bone matrix (Pritchard 1972a).

Osteocytes are osteoblasts that have become trapped in the hardening matrix of their own making. Although there are variations in size and shape, generally these are plump cells with numerous branching cytoplasmic processes. Pritchard (1972a) describes them as spider-like. These cells occupy the previously discussed lacuna within the matrix. As mentioned, radiating from these lacunae are canaliculi, or small fine tunnels within the bone that carry the cytoplasmic processes (McLean and Urist 1968). The processes anastomose freely to give bone its complex system of blood vessels. Although there is debate about the function of the osteocytes, one current belief is that they facilitate material exchanges between the bone and outside tissue. Belanger (1969) suggests that osteocytes even manufacture and resorb their immediate matrix, a process he calls osteolysis. Another current opinion is that the osteocytes are involved in the regulation of the calcium concentration in the body's fluids (McLean and Urist 1968). Whatever their function, it is concluded that a single osteocyte is responsible for approximately 100 micrometers of surrounding bone tissue (Pritchard 1972a).

The life span of the osteocyte is not known; however, empty lacunae can be found in the bones of the elderly or after skeletal

injuries. Finally, it has been suggested that the matrix in the immediate area of the osteocyte is different (Weidenreich 1930 in Pritchard 1972a), perhaps fiber-free or hypermineralized (Mjör 1962). However, Vose and Baylink (1970) in a more recent paper, feel that the fibers around the osteocyte are simply oriented in a different fashion.

The cell responsible for bone resorption is the osteoclast. Osteoclasts are found both during normal physiological remodeling; such as that which occurs during embryological growth; and pathological remodeling, which may be seen during a number of disease processes. The cell is large and multinucleated. Osteoclasts are characterized by a brush, or ruffled, border which occurs on the side of the cell in contact with the bone surface undergoing erosion. Along this surface also lie resorption pits, or depressions in the bone. These are known as Howship's lacunae and they house the osteoclast during its work (Hancox 1972).

It should be noted that these cells are not present in all vertebrates. The bones of some of the higher orders of the Teleost fish are acellular. Even though such bone has the chemical, physical, and histological properties of mammalian bone, it has no lacunae, canaliculi or osteocytes (Simmons et al. 1970).

FORMATION OF BONE

Although various processes are constantly contributing to the growth and remodeling of a bone during life, during embryogeny the

skeleton is formed one of two ways, either by intramembranous or endochondral formation. The first refers to formation in membrane, while the second refers to formation within cartilage (Vaughan 1981).

Intramembranous ossification can best be exemplified by the growth of the fetal cranial vault. DeKleer (1982) describes the embryonic skull vault as having its blueprint in membrane sheets as opposed to a cartilage model. First, according to McLean and Urist (1968), in this area of the developing skeleton, in the cells of the connective tissue where bone will eventually appear, there is a thickening. The tissue becomes more homogeneous. At this time the tissue cells experience a size increase and become osteoblasts. These osteoblasts then secrete osteoid and, at this point, can be regarded as centers of ossification (Vaughan 1981). Calcification begins at this point in the matrix.

Formation of bone from a cartilage model is termed endochondral ossification. This type of ossification occurs throughout most of the fetal skeleton (McLean and Urist 1968). Following a condensation of mesenchyme, the peripheral cells of this condensation become oriented in the form the bone will take. This outline is called the perichondrium. This calcifies, leaving periosteal bone as a collar around a cartilagenous model. Meanwhile, in the center of the model, the cartilage cells are undergoing various changes that will ultimately lead to calcification (Vaughan 1981). These changes include proliferation, maturation, hypertrophy, and degeneration (Fawcett 1986). The degeneration of the cartilage cells allows for their replacement (Vaughan 1981).

GROWTH OF BONE

There are two patterns of growth that occur in the developing bone until adult dimensions are reached. The first increases the length of the bone, while the second increases the girth (Vaughan 1981). Growth in length is accomplished through endochondral ossification occurring at each end of the bone. The epiphyseal cartilage undergoes cell division. Cells on the diaphyseal side of the cartilage are replaced by bone, while new cartilage cells are generated on the epiphysis side of the cartilage. This allows the cartilagenous plate of the epiphysis to remain roughly the same size while increasing the diaphyseal length of the bone (McLean and Urist 1968).

Growth in the diameter of the bone occurs by apposition. For example, in this manner new bone is laid down on the existing periosteal surface. Resorption from the inside, on the endosteal surface, maintains the geometric shape of the bone while increasing its girth (Vaughan 1981). This process of deposition and resorption is also seen during remodeling, a normal process of alterations to bone structure required by function and use (Lanyon and Rubin 1985).

CONCLUSION

Knowledge of bone structure is necessary for the following discussion of the mechanical characteristics of bone. The reaction of bone to the pertinent methods of modification, boiling or roasting, is made more clear when prefaced by a discussion of bone anatomy.

CHAPTER 3

THE MECHANICAL PROPERTIES OF BONE

To analyze a fragmented specimen, one should know something of the structure and characteristics of the object as a whole. For example, before a small bone fragment can be identified as humerus or femur, it is necessary to know which features are diagnostic of each element. In this manner, before fracture patterns in bone can be studied, the mechanics of fracture and how they apply to skeletal material must be outlined. Thus the following chapter summarizes basic mechanical concepts, the mechanical characteristics of bone, the fracture process, and previous studies of bone and bone fracture in the biomechanical field.

BASIC MECHANICAL CONCEPTS

One of the most fundamental mechanical concepts is that of force. According to Frost (1967), force can be defined one of two ways. In the first definition, force is considered to be that which can cause matter to accelerate while in the second, it is considered the resistance to acceleration by matter. Force as described in the latter definition is referred to as inertia.

Commonly, in biomechanics, force is then divided into two categories. Loads are forces that come from outside of a structure; stresses are generated within the substance of the structure by the

loads. In this manner, a load is any force, or combination thereof, that is placed on the exterior of a structure and, thus, supported by that structure. Load can be expressed in two manners, either as the unit load or the total load. In the unit load, force is expressed per unit of area. In this manner, if one square inch (in.^{2}) has 5 pounds resting on it, then the unit load is 5 pounds/in.^{2}. If 5 square inches have 25 pounds of force in contact with them, the unit load is still considered to be 5 pounds/in.^{2}. The total load is, simply enough, the total load borne regardless of area. Thus, in the above examples, the total load is 5 and 25 pounds respectively (Frost 1967).

As already mentioned, stress is the force produced within a material in response to the application of external loads. It is the resistance of the intermolecular bonds within a material to deformation caused by loads placed on the exterior. Three principal stresses are recognized. Any kind of physical load generates stresses that can be described as some combination of the three. The first principal stress is tension stress, which is a resistance to being pulled apart. When a muscle contracts, it causes tension stress within its tendon. Compression stress is the second. This stress is generated in a structure which resists being pushed together. An example of this type of stress can be seen in the bones of the leg, which resist being squashed when an individual stands and places his body weight upon them. The third principal stress is shear stress. This can be seen in the resistance of paper to being cut by a pair of scissors (Frost 1967).

As with loads, stress is expressed in two ways: total stress or

unit stress (Frost 1967). These labels shall not be discussed further, as they are not used in the current work. However, it should be noted that stress cannot be measured directly. Other types of information must be used to compute stress. These include direct measurement of the load applied, using a strain equivalent, or photoelastic analysis.

Any sort of load applied to any sort of object causes deformation. This deformation may be clearly visible, such as the bend in a tree branch if one pulls on it; or, special devices may be required to sense the deformation, such as when a lizard scurries over a rock. Regardless of load size or strength of the object receiving the load, deformation will occur. This deformation should be referred to as strain (Frost 1967).

As with stress, there are three principal strains. These are analogous to the principal stresses and include tension, compression, and shear strain. Tension strain is elongation. A piece of stretched fabric exhibits tension strain. When a tennis ball is hit with a raquet and squishes inward, it is exhibiting compression strain. Shear strain is seen in an object that has a portion of itself displaced sideways with respect to the remainder of its structure (Frost 1967). These strains are represented visually in Figure 2.

Strain, like stress, can be measured either as total or unit strain. These measurements may be made directly with strain gauges, with stress coats, or photoelasticity. These shall not be discussed here as a measurement of strain was not made in this work. Further information can be found in Frost (1967).

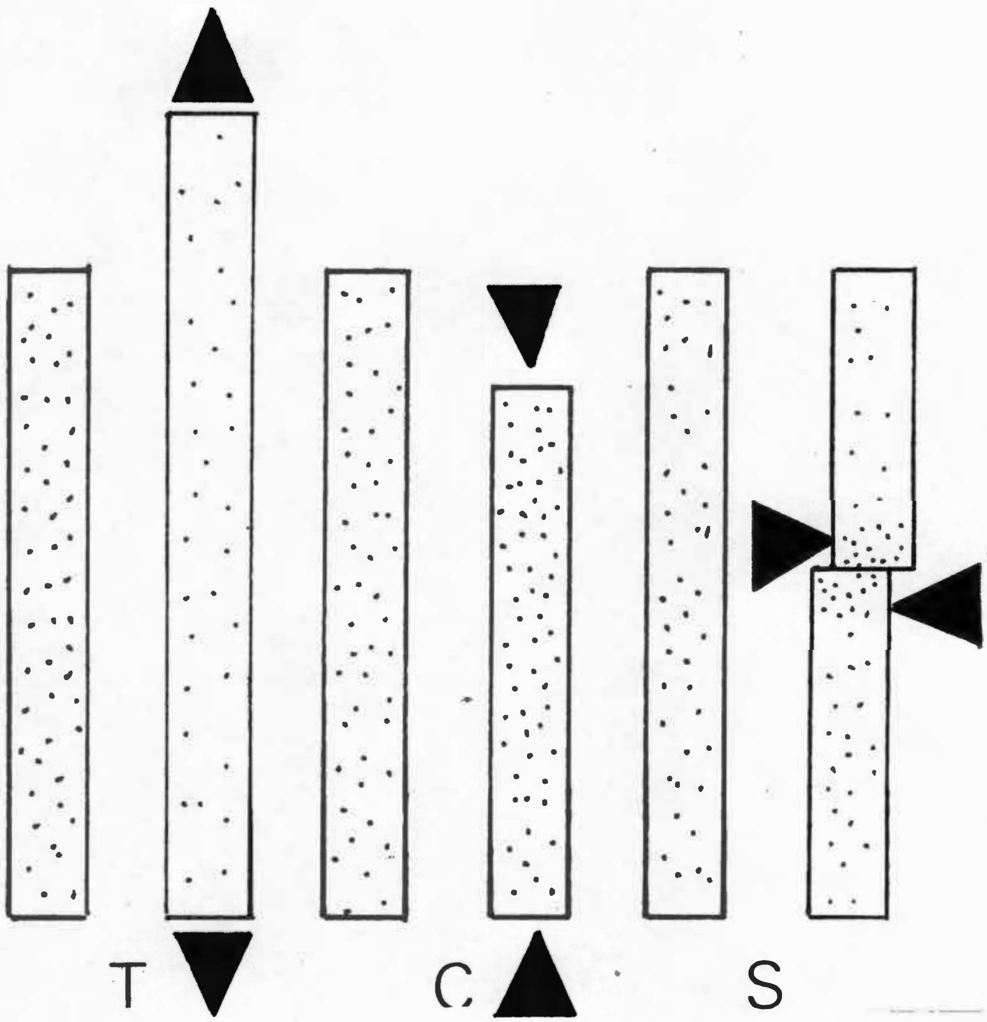

Figure 2: The three principal strains:
tension, compression, and shear.
These are analogous to the three principal stresses.
Adapted from Frost (1967).

THE RELATIONSHIP OF STRESS AND STRAIN

The study of stress and strain has revealed a relationship between the two which has its own vocabulary. Stiffness is defined as the resistance of a substance to being strained. It is measured by dividing the stress by the elastic strain. This measurement is called Young's modulus (or Young's modulus of elasticity). A stiffer material has a large modulus. However, a large modulus does not automatically suggest strength. Chalk is stiff but not strong (Frost 1967).

In reality, materials may experience all three of the principal strains simultaneously. Given that in the real world, nothing is simple, it can be expected that these strains are not always equal. Hence, there are separate moduli, including a tension, compression, and shear modulus. Some metals and plastics exhibit nearly the same moduli in tension and compression (Frost 1967); however, most materials, including bone, exhibit different properties depending on the direction of measurement. These types of materials are termed anisotropic (Currey, 1984).

A material is elastic if, once strained, it returns to its original shape when the stress is removed. A tennis ball can be used again as an example. When stepped on, it shortens in compression; if released, it rebounds to its original shape (Frost 1967).

In some materials, strain increases proportionally to stress. These materials are subject to Hook's Law and are known as Hookean solids. In such a material, if the strain is tripled, so is the

stress. If there is a reduction in stress, a similar reduction in strain occurs (Frost 1967).

Resilience is a property displayed by a material that returns to its original shape as quickly as it deforms. Resilience can be seen as a degree of elasticity (Frost 1967). Its opposite is called damping, in which impact force is damped out, and the material does not regain its shape with ease. Frost (1967) feels that dry bone is more resilient while wet bone is a damping material.

Lastly, toughness is defined as resistance to fracture. Bone is considered a tough material (Frost 1967).

STATICS

According to Frost (1967), statics is the study of objects in which the stresses and strains balance so the object will not accelerate. Single bones with applied loads such as those in this study are examples of static structures, hence, a brief discussion of the distribution of stresses and stains in such materials is in order. Generally, there are three primary types of loads on solids and a fourth class that is combined. The former three include uniaxial loads, bending, and torque, while the latter is simply some combination of the three (Frost 1967). A discussion of bending is of most importance to this work although the others will be briefly summarized.

An idealized uniaxial load produces stresses that are even throughout the item. These loads can cause compression, tension,

and shear strains as well as stresses, but the load is centered over the structure and in line with its axis (Frost 1967). Torque is simply twisting (Frost 1967). Had the crack-and-twist method been used in this study, torque would be a factor. Combined loads include combined compression and static bending, pressure in closed containers, and bending and torque together (Frost 1967).

Bending can occur in two ways, either as pure bending or three point bending. A beam supported at either end and subjected to loading in the middle such as the bones in this study is subjected to three point bending (Carter and Spengler 1982). In this situation, tension, compression and shear stresses all play a part. In this bent beam, tension stresses and strains can be found in the bottom of the beam parallel to the length. Compression occurs in the upper portion, again parallel to the length. The beam is divided into upper and lower halves by the neutral plane. There is no tension or compression stress or strain at the neutral zone. Both vertical and horizontal shear is at work. Vertical shear is equal throughout the beam while horizontal shearing stress and strain is greatest at the neutral plane and zero at the top and bottom (Frost 1967). Figure 3 depicts a beam undergoing three point loading and its accompanying stresses and strains.

THE PHYSICAL BEHAVIOR OF SOLIDS

Solids, including bone, have some properties in general. Before looking in depth at the properties of bone, some general properties

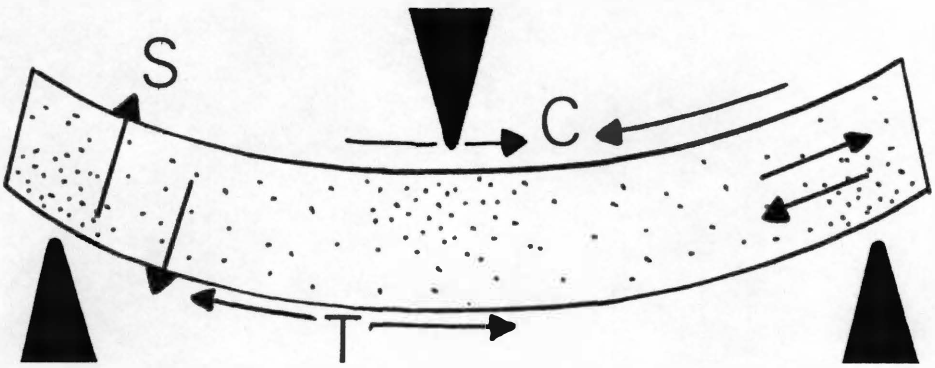

Figure 3: A beam in three point loading.
Adapted from Frost (1967).

shall be mentioned.

One property is that of the proportional limit. When a load is placed on a beam, strain will be roughly proportional to the stress, at least for a time. During this time, the material is performing as a Hookean solid. However, eventually, with an ever-increasing load, a time is reached when the strain increases faster than the stress. The point at which this occurs is the proportional limit (Frost 1967). Bone does behave as a Hookean solid.

A material may be deformed past its proportional limit and still, with the removal of the load, return to its original shape. This hypothetical material is behaving elastically. But with further increase of the load, the material will be loaded beyond its elastic limit and will remain deformed following removal of the load (Frost 1967). This residual deformation is referred to as plastic strain (Currey 1984). Ductility is the ability of a material to flow plastically when loaded without breaking (Frost 1967).

The ultimate strength is the highest load a structure can bear. When a material reaches its yield point and begins to stretch, it eventually breaks. This point is called the rupture strength. For bone and other brittle materials, the rupture strength and ultimate strength is similar (Frost 1967).

Repeated use of a material can cause fatigue or creep. Fatigue is "breakage caused by repeated loading and unloading within the apparent design limits of the structural material" (Frost 1967:39). Creep is the tendency for materials to gradually give or behave plastically following repeated cycles of use (Frost 1967).

In review, bone's proportional limit, rupture strength, and ultimate strength is nearly the same. There is some disagreement about the exact classification of bone at this point. According to Frost (1967), bone is a brittle material. However, true brittle materials fracture with a smooth surface; bone generally does not and so cannot be regarded as truly brittle (Currey 1984). Carter and Spengler (1982) state that bone is a viscoelastic material. Currey (1984) prefers to call bone a fibrous composite. This means that bone deforms only a little before breaking, unlike ductile metals which stretch. I prefer this latter definition.

Bone's tensile strength is roughly 12,000 pounds per square inch (psi). Stronger in compression than tension, it can support approximately 15,000 psi when under a compressive load. Its shear strength is only 4,000 psi, and it exhibits a Young's modulus of roughly 2.8×10^6. These figures were measured parallel to the grain (Frost 1967).

FRACTURE MECHANICS

The relationship between stress and strain can be visualized from a load-deformation curve, produced by monitoring the load placed on, and the deformation of, a specimen. An example of this curve for a hypothetical bone can be seen in Figure 4.

Stress is plotted on the y-axis while strain appears on the x-axis. At first, the strain rises with the stress. Here the material is acting as a Hookean Solid. Some biological materials have little to no

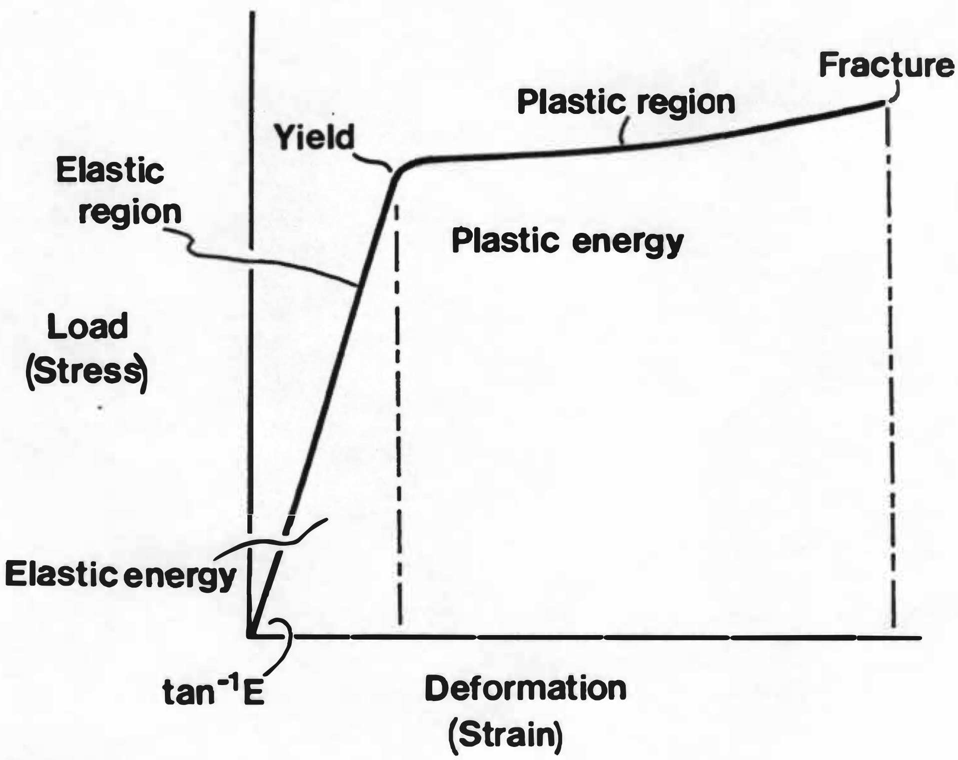

Figure 4: An example of a load-deformation curve for a hypothetical bone.
Taken from Currey (1984:10).

proportion between stress and strain, for example, cartilage (Currey 1984). Bone, on the other hand, does tend to briefly act as a Hookean Solid (Frost 1967). At the top of the curve is the yield point where deformation changes from elastic to plastic. As previously mentioned, in the elastic region, if the load is removed, the bone will return to its original form. Once there is entry into the plastic region, the material will be deformed permanently or must heal in order to return to its original shape. In the plastic region, strain increases faster than stress. For bone then, there is little difference between the yield stress and the fracture stress. Fracture stress can be thought of as the ultimate strength of the bone (Currey 1984).

PREVIOUS BIOMECHANICAL STUDIES OF BONE

Previous studies in the biomechanical field of bone behavior and fracture characteristics are many and diverse. The studies examine bone from a range of hosts, most notably humans and bovines, with both standardized specimens and whole bones being tested. Observations include tensile and compressive strengths utilizing various types of loading techniques, explanations for strength variation, and hypothetical musings about the nature of bone. The following review of literature is by no means an exhaustive list but gives an idea of various concentrations of bone research. Various reviews by researchers in the field can be found (see Sedlin and Hirsch 1966; Smith and Gilligan 1989).

In 1987, an outline of the history of bone biomechanics and

some of its fundamental concepts was presented. According to Roesler (1987), bone was initially examined as a structure. This concept of bone affected research from the 1600s through the middle of the 19th century. Bone was then examined as a material, and, lastly, in the most recent 25 years, as a system.

In keeping with the concept of bone as material, Currey (1964) puts forth three analogies as explanations for the mechanical properties of bone. In the first, he examines the idea of bone as a compound bar, such as reinforced concrete, wherein steel acts to increase the load-carrying capability of the concrete by the sum of its resistance. This idea he rejects, stating that bone has a higher strength than expected when the sum of the loads expected to be borne by the collagen and apatite are figured. A second hypothesis is that of bone as a prestressed material. Prestressed beams consist of steel wires under tension with the concrete around them in a state of compression. Knese (in Currey 1964) suggests that in bone, collagen is in a state of compression while the apaptite is in a state of tension. Upon review, Currey negates this hypothesis and states that as an answer to explain the "peculiar properties of bone" (Currey 1964:6), prestressing does not do an adequate job. Finally, in the third analogy, he asserts that bone consists of a matrix with a low modulus of elasticity while the crystals embedded within have a high modulus. This is most similar to a two-phase material such as fibre-glass which has glass fibres contained in an epoxy resin. One characteristic of two-phase materials is anisotropy. Currey concludes by stating that two-phase materials are not rare among biological

materials.

As mentioned previously, whole bones have been studied as well as smaller specimens. Some of the smallest specimens studied have been single osteons. Ascenzi and Bonucci (1964) dissect small ground specimens of bone in order to study the ultimate tensile strength (UTS) of such units. Various osteons are tested, including wet and dry samples, and irregularly calcified units. They conclude that dry osteons have greater strength; the orientation of the collagen fibers affects strength more than degree of calcification; age does not seem to affect strength; human and ox samples have the same strength; and the actual mechanical unit in compact bone appears to be the osteon. A later study, however, (Ascenzi et al. 1982) finds differences in thickness both between and within lamellae. This variation may explain the absence of significant difference for ultimate tensile load based on degree of calcification.

Ascenzi et al. (1990) also examine the bending characteristics of single osteons. This time the authors test osteons with the same degree of calcification but differing collagen orientation. The first type tested shows longitudinal lamellae with courses all running in longitudinal spirals. The second type, called alternate, shows longitudinal spirals alternating with nearly transverse spirals. The samples are subjected to bending tests. Results indicate that longitudinal samples deform more prior to fracture and experience more bending strain. Thus, it is inferred that alternate osteons can withstand bending better than longitudinal. According to Vincentelli and Evans (1971), however, bone with a greater percentage of

longitudinal lamellae has higher UTS than that with alternating lamellae.

Variations in bone with age has been another subject of research. Legros et al. (1987) study mineral content in cortical bone samples of rats (ranging from newborn to adult), calves, and cows. It is observed in both groups that apatite crystal size increases with age as does the calcium/phosphorus ratio and carbonate ion content. Other authors (Wall et al. 1979) find, from work with human femoral bone, that UTS and density of bone increase with age up to around the age of 40. After this time, there is a decrease in both with age. Strength decreases at a faster rate than density. In other words, density of bone is not the only contributor to its strength. A similar study by Melick and Miller (1966) also found that UTS decreases with age, with a significant difference found between those under age 60 and those over. A significant change in calcium or ash content is not observed.

Several studies have examined strength variation in human bone as a function of both age and sex. Mather (1968) uses whole femora for experimentation. Observations show that the bending strength of the female femora is significantly less than that of the male femora. Mather postulates this is due to the smaller dimensions of the female elements. Both sexes experience a decrease in breaking strength with age. Lindahl and Lindgren (1967), on the other hand, in their study of human femora and humerii, find no significant difference between the sexes in regards to the mechanical properties. Not unexpectedly, they too report a decrease in strength with age.

(As an aside, the humerus has a significantly higher UTS than the femur.)

Fatigue damage to bone, although not a consideration for the experimental study described here (despite Johnson (1985)), has been researched in the biomechanical field. Sections of beef femora are repeatedly subjected to rotating bending loading by Carter and Hayes (1977). Such fatiguing of bone tissue leads to a progressive loss of both ultimate strength and stiffness. Such behavior is also seen in composite materials. In these latter materials, fatiguing is supposed to stem from microcracking, debonding, breakage of fibers, and void growth. In agreement, Caler and Carter (1989) state that mechanically, bone response to fatigue-creep is poor. Following an experiment with living dogs involving repetitive loading, Burr et al. (1985) state that microdamage of bone caused by fatigue contributes significantly to the initiation of osteonal remodeling. Prior to fatigue, however, bone exhibits considerable yielding, or plastic behavior (Burstein et al. 1972).

In studies peripherally related to the study by Burr et al. (1985), various components that contribute to the actual architecture of the skeleton are examined. Carter (1987) proposes that stress histories are a controlling factor in the biology of connective tissues. Lanyon (1987) suggests that where shape or protection is most important, bone structure will be controlled by the genes. Where repetitive loading is most likely to occur, functional strain contributes to architecture. This is stated earlier by Rubin (1984) who proposes that soft tissues such as muscle and tendons work with calcified tissue in

order to produce a "restricted strain environment" (Rubin 1984:S11). The individual bone and its structure are described by both Amtmann (1968), who examines breaking strength in the human femur and its distribution throughout the bone, and by Evans and Lebow (1952), who examine the physical characteristics of the femur by thirds, separating anterior, posterior, medial, and lateral. Pope and Outwater (1974) report that changes in strength and elasticity of bone are related to distance from the eipiphyses. This may be due to the way osteons are oriented in this area.

Several studies examine the strength and fracture of bone and how it is effected by various components of the bone itself, including mineral content, porosity, density, and bone structure. It is stated that both density and porosity have an effect on the stiffness of compact bone (Schaffler and Burr 1988). Currey (1988) finds calcium content and porosity to be linked to the modulus of elasticity. The pattern of the collagen fibers has an effect on the tensile stress present at fracture, as well as how the fracture propogates (Simkin and Robin 1974). Several authors (Currey 1959; Evans 1978; Evans and Vincentelli 1974) agree that the presence and number of Haversian systems within a portion of bone has a negative correlation with compressive, torsional, and tensile strengths. According to Lakes et al. (1990), bone with microcracks due to fatigue or surgical cuts is stronger than expected. This may be due in part to the fact that the cement line between osteons and matrix will allow crack initiation but seems to slow crack growth (Burr et al. 1988).

Due to the fact that many studies use only small specimens of

bone machined from larger elements, observations have been made about how specimen orientation, density, and thickness can effect the experimental properties that are then applied to whole bones. The stiffness of bone is affected by the angle of the cut of bone to the longitudinal axis (Hirsch and Da Silva 1967). A small increase in density is related to a greater increase in strength while specimen thickness is not a significant factor (Wright and Hayes 1977).

Temperature and its effect on bone has been another area of study. Amprino (1958), as just one part of a larger study, determines that microhardness of bone increases with temperature up to 120° C. There is a decrease between temperatures 300° to 500° C, with microhardness increasing again after temperatures of this level. Armstrong et al. (1971) note that compressive strength of bone specimens increases at temperatures below 0° C. It is also observed that Young's modulus in bone increases as temperature falls (Bonfield and Li 1966). Boiling of bone in order to observe the effect on bone collagen is performed by Bonar and Glimcher (1970). Both the "short-range (helical) and long-range (the packing of collagen macromolecules...)" (Bonar and Glimcher 1970:545) structure of collagen is examined following thermal denaturation. In demineralized bone, collagen will shrink depending on height of temperature; the short-range structure of collagen is disrupted for several hours; and the long range order is lost entirely if the heat is too high. Garrett and Flory (1956) also see collagen melt at higher temperatures, then recrystallize following several days.

A plethora of studies simply reporting various aspects of bone

strength and fracture characteristics can be found. Using bovine bone, Bonfield and Datta (1974) determine Young's modulus for compact bone. Reilly et al. (1974) also examine the elastic modulus of bone using human and bovine bone. No difference in the modulus is found despite both tension and compression tests being used. Pope and Outwater (1972) examine the fracture energy and toughness of bones, including bovine, canine, and anthropoid bone. All specimens used are precracked, that is, a short crack is started in the material prior to fracturing in order to lessen the energy required to start the fracture. Wood is also examined in this study so that a comparison between bone and another fibred substance can take place. Piekarski (1970) conducts much the same kind of tests, however, no precracking is initiated. Bonfield and Li (1966), among other aspects of their study, note that plastic strain in bovine bone is not all permanent as there is a large anelastic contraction following unloading of the specimen. Lastly, Martens et al. (1986) describe several different fracture patterns in femora subjected to bending.

CONCLUSION

In this chapter, the mechanics of fracture and how they apply to skeletal material are outlined. Previous studies of bone, its mechanical characteristics, and fracture behavior are outlined. This brief summary points out the many factors influencing bone's reaction to modification.

CHAPTER 4

MATERIALS AND METHODS

Femora from domestic swine were used in this study of fracture patterns. One half of the total sample was experimentally broken by the author and then subjected to macroscopic analysis. Results were subjected to several statistical tests. The SEM was used to view several specimens. The remainder of the total sample was fractured using an Instron stress testing machine from the Engineering Department at the University of Tennessee, Knoxville. These latter bones were used solely for the purpose of determining the relative strengths of the groups involved.

MATERIAL

To study fracture differences, a total of 180 domestic pig (Sus scrofa) femora was obtained from a local meat processing plant. These bones had already had the majority of flesh removed with the exception of the periosteum and the patellar tendon and associated tissue near the knee. They were collected in multiples of thirty and refrigerated prior to their use. No bone had been kept for longer than two weeks at the time of its use and the majority were used within six days of their collection. It was decided to keep the skeletal elements fresh instead of freezing them. Although freezing does not alter the histological appearance of soft tissue (Baraibar and Schoning 1985),

nor does it seem to alter the mechanical properties of bone (Sedlin 1965), it was felt that it would be more appropriate to have fresh specimens. Johnson (1985) states that a majority of researchers, including Bonnichsen (1979), and Sadek-Kooros (1975) among others, have used frozen bone thawed for their experiments.

Domestic swine was chosen as the experimental group in this study for several reasons. Perhaps the most important was the availability of the element. Lay's Packing Co., Inc., a local meat-packing plant, was more than helpful in providing a steady supply of Sus scrofa femora. Also a relatively homogenous sample is represented as a result of the similar age and weight grade of the animals involved. Although the animals are not harvested at a specific age, they are cropped when they reach a live weight between 230 and 240 pounds (David Carter, personal communication 1992). Although exact ages may vary slightly across the sample, all animals are immature as evidenced by the lack of complete epiphyseal fusion.

In addition, pigs were a relatively common food source on both historic urban and rural sites (Reitz 1986). Thus, pig bones will often be present in the historical archaeological record and offer a chance for an application of the method presented here. The femora of food animals are also consistently modified, due to the large amount of marrow present in the element (Gilbert 1990). Also, similarities exist across mammalian species both in the general makeup of their bony skeleton, i.e. presence and placement of apatite and collagen, (Currey 1964) and in the mechanical characteristics thereof (Ascenzi and Bonucci 1964). Thus, should the opportunity arise, there is a chance

for the method to be applied to skeletal material other than swine. It is expected that this method will be fully applicable across mammalian species, including humans.

THE SAMPLE GROUPS

All patellae were removed from the femora prior to breakage in order to facilitate the fracture process. The bones were then divided into two groups of ninety. Within these groups of ninety, there was a further division into three groups of 30. One group was left fresh, one boiled, and the third roasted. These divisions are shown below

Treatment	Sample Size
Fresh	30
Boiled	30
Roasted	30

and represent the samples for the hand-fracturing and the mechanical testing.

The first group, or control, was broken in a fresh state without modification. A second series was boiled for 2 hours and then fractured. In order to minimize variations in the time the water took to heat, this group was placed in the water once it had already reached a rapid boil. Of the boiled bones broken by hand, 15 were

broken immediately and 15 were allowed to cool for 2 hours, 45 minutes. The third group was roasted in an oven for 1.5 hours at 176 degrees centigrade (C).

One minor exception was those roasted bones utilized in the manual fracturing process. These were roasted near the coals of a mixed wood fire. The first six of these bones were roasted for 30 minutes. The remaining were roasted for twenty minutes. Five temperature readings were taken at the base of the fire as well as from eight bones placed at a number of positions during the roasting process. Temperatures for the fire ranged from 206° C to 573° C, with an average of 442° C. The range of temperatures for the bones was 38° C to 221° C, with an average of 129° C. All readings were taken using a pyrometer made by the Thermolyne Corporation of Dubuque, Iowa. The instrument has a centigrade temperature span of 10°-1093° with 1 degree of resolution and an accuracy of +/- 0.5% of the reading. All bones cooled for at least 5 minutes before being fractured. During the actual roasting, six bones fractured on their own from the heat. To remedy this, extra bones were roasted until a total of 30 could be broken by hand.

It was decided to roast the hand-fractured bones in this manner in keeping with ethnographic descriptions. Binford (1981) notes that bones broken by the Nunamiut for marrow are first placed close to the coals of a fire. Zierhut (1967) observed the Calling Lake Cree of Canada warming marrow bones near the coals of their fires. They report this makes the bones easier to break. Bonnichsen (1973) suggests this is to remove the periosteum and by doing so, weaken

the bone. Time constraints did not allow the bones used with the Instron to be roasted in this manner.

MECHANICAL TESTING OF BONE

The Instron stress testing machine was used for several reasons. First, as mentioned in the introduction, it was found during experimental breakage by hand (Horwitz 1987; William Whitehead, personal communication 1992; Woltanski 1990), that boiled bone was much harder to break than fresh bone. As previously summarized, William Whitehead (personal communication 1992) found while using an Instron immediately after boiling, bone could withstand nearly 20,000 more pounds per square inch (psi) prior to failure than fresh bone. In an effort to replicate Whitehead's results and to put a quantitative form to the observation that boiled bone is harder, the Instron was utilized in this study. Whitehead's sample consisted of 4 inch shaft sections; in contrast, whole bones were employed in this study.

The elements broken by the Instron were subjected to 3 point loading (See Figure 5). For example, each bone was supported on two rollers 4 inches apart with the distal epiphysis toward the operator while a third roller pressed down on the posterior side of the element from above. The roller exerting pressure moved at a speed of 1 inch per minute. Beneath the supporting rollers was a load cell which registered the force exerted in pounds. A chart, moving 0.5 inch per minute, recorded the load-deformation curve.

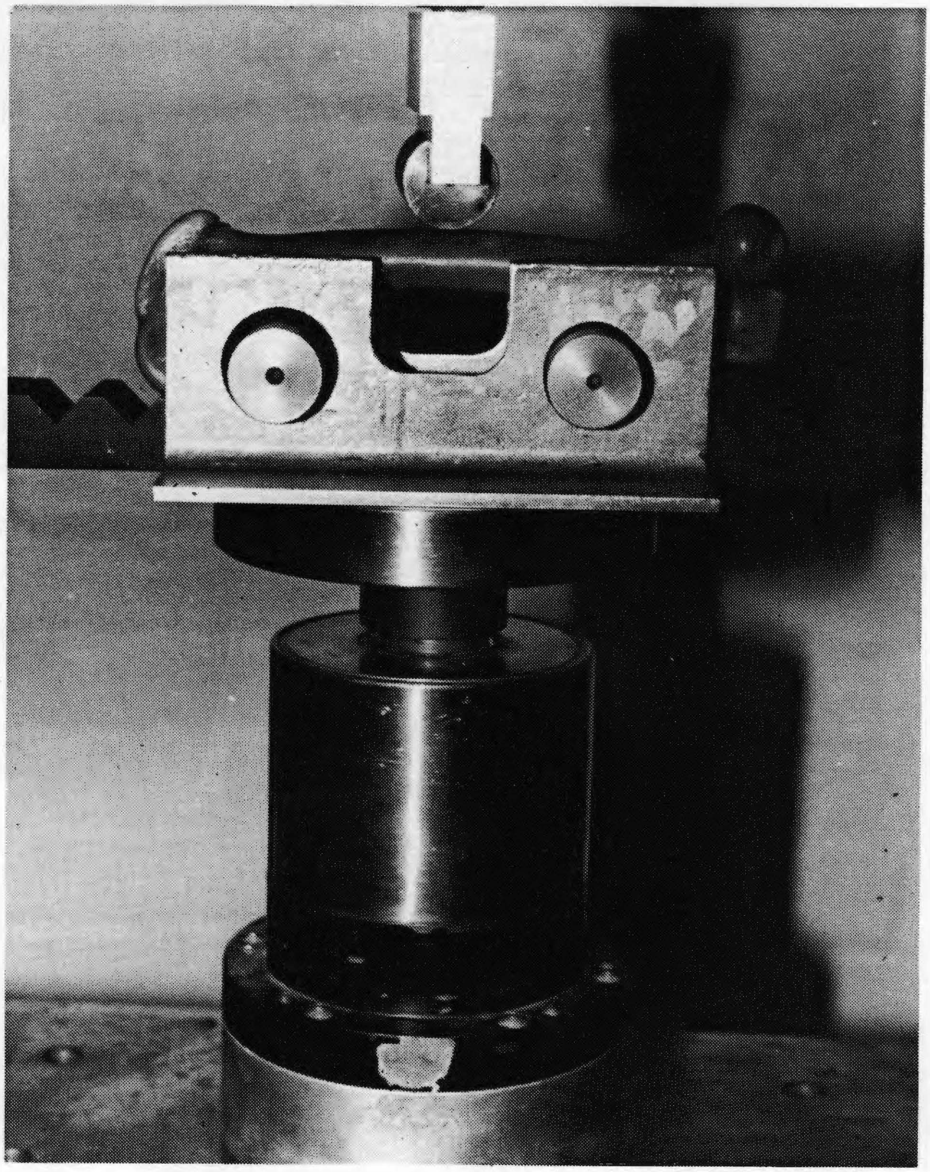

Figure 5: Bone being subject to three point loading by the Instron. Orientation of experimental specimens was slightly different than that pictured above.

The general shape of the curves was compared as well as the behavior of the bones during the process. The loads determined for each group were submitted to statistical analysis. Loads were not measured in psi, but were simply the total load borne by the element.

The bones fractured by the machinery were not used for macroscopic analysis. The Instron fractures by slow loading of an element, while fracturing by hand produces rapid loading. Loading rapidity is actually quantified by observing the strain rate (Carter and Spengler 1982); however, in this study it was done intuitively. According to Carter and Spengler (1982), traumatic bone fracture is considered rapid loading. Smashing the midshaft of an element with a hammerstone qualifies as traumatic fracture. A load moving at 1 inch per minute, such as the Instron, does not constitute such a fracture. Speed of loading can affect the fracture pattern produced (Nordin and Frankel 1980). A bone loaded rapidly will absorb far more energy than one loaded slowly (Carter and Spengler 1982). Thus the energy released into a bone loaded slowly may be dissipated through a relatively simple single fracture while rapid loading will cause more complex and numerous fractures (Nordin and Frankel 1980). Given that the bones found in the archaeological record would most often have been broken by rapid loading, the hand-fractured group was chosen for closer analysis.

THE HAND-FRACTURING PROCESS

Binford (1978, 1981) in his ethnoarchaeological work with the Nunamiut, notes that bones broken to remove marrow are generally fractured one of three ways. First, the bone may be hand-held and a percussion tool used to strike it. Second, the bone may be struck across a hand-held anvil; or third, it may be struck across a stationary anvil rock. Bonnichsen (1979:36), during his experimental work, for the most part utilizes two variants of what he calls "the mid-diaphysis smash technique." The first variant consists of placing an anvil directly under the center of the diaphysis while in the second, two supports are placed under the epiphyseal ends of the bone. The bone is then loaded in the midshaft area. The latter variation of this technique was observed among the Calling Lake Cree of Alberta by Zierhut (1967).

The bones in this study were placed with the epiphyseal ends resting on two pieces of wood each 72 mm in height. This left the midshaft unsupported in the middle. The posterior surface of the bone faced the ground and the anterior face was the surface first impacted. A stone weight, weighing 2.95 kilograms, was used to load the midshaft area. The author knelt or sat cross-legged before the bone raising the weight above shoulder height. This technique is illustrated in Figure 6. The number of blows required to break the bone completely through were recorded. The highly touted crack-and-twist method was not used.

It is known that different fracture patterns result from the

Figure 6: The author at work fracturing one of the experimental bones.

various breaking strategies (Binford 1981; Sadek-Kooros 1972; Woltanski 1990). Therefore, because the intent of this study was to isolate the method of pretreatment, all bones were broken using exactly the same technique.

All fragments of each fractured bone were collected, and each bone placed in a nylon net bag and tagged with an experiment number. The fresh bones were placed in a large pot with a small amount of BIZ bleach and water and gently warmed over a period of several days to allow ease in removal of any remaining flesh. The boiled bones were left as they were following breakage. The roasted bones were soaked for several days but care was taken as the material was slightly more fragile. All bones were placed on racks to dry. Once dry, they were again bagged in clean, dry nylon netting to keep all pieces together, and to discourage mold growth.

MACROSCOPIC ANALYSIS

Once the fractured femora dried, analysis began. A macroscopic analysis was conducted with all observations for each bone entered on a recording form (see Appendix A). First, the total number of fragments per specimen was noted, as it was observed by Woltanski (1990) that boiled bone tended to fragment more than fresh bone. Maximum number of fragments also varies with breakage technique (Noe-Nygaard 1977; Sadek-Kooros 1972). This could ultimately affect the number of identified specimens (NISP). Detached epipyses were not included in this count.

Next all fragments were analyzed separately in order to approach most closely the situation encountered in the field and laboratory. Initally, all bone specimens were oriented in the same manner in order to allow replicability. This orientation procedure was first used by Bonnichsen (1979) and later by Davis (1985). First, a piece of graph paper was placed on the surface where the analysis was to take place. A line parallel with the Y axis was drawn. The bone fragment was then placed with the fractured end toward the analyst, with the side displaying the majority of the marrow cavity upwards, and the penciled line bisecting the specimen. However, it was found that the most accurate observations were obtained if the bone was simply held in the hand and rotated to allow visual access to all sides. If an impact site was present on a fragment, it was noted and scored along a continuum ranging from 0 to 4. A score of 0 was assigned when no sign of an impact was present, while 1 represented an impact seen as fragment removal from the shaft. A score of 2 corresponded to the presence of concentric ring fractures. A concentric ring fracture is defined by Bonnichsen (1979:40) as a "semi-circular crack which outlines the outside dimensions of the impactor." In addition, occasionally, a negative scar which undercuts the wall of the bone may also be present. Both the presence of concentric ring fractures and negative scars warranted a score of three, while four was given when a crush fracture represented the impact site.

Following a review of anthropological literature, it was seen that fracture classification was problematic. Although many authors discuss spiral fractures, few definitions of such can be found. In

addition, the terminology of fractures was rarely found to be consistent between authors. For example, Bonnichsen (1979) refers to spiral fractures, while Haynes (1983) prefers the label helical fratures. Davis (1985), in order to combat what she feels is over-simplistic terminology, labels spiral fractures as oblique. Johnson (1985) differentiates between spiral fractures in fresh bone and diagonal fractures in dry bone (horizontal tension fractures) but does not explain how to tell the difference. Several authors (Davis 1985; Haynes 1983) prefer to describe fracture morphology independently for all sides and utilize this for classification purposes (Davis 1985). Although this results in a very clear description of the bone, I feel it is also a more cumbersome classification scheme. I felt it would be preferable at this point in the study to concentrate on a scheme that would classify the more general appearance and orientation of the fracture. Thus in an effort to find a more clear definition of fracture types and, hopefully, a replicable method of classification, the medical literature was consulted. Medical practitioners most often refer to three specific types of fracture for the long bones; transverse, oblique, or spiral; although their definitions were occasionally vague (Ralston 1967) or nonexistent (Betts-Symonds 1984). A radiology text seemed to shed the most light (Rogers 1982). Four types of fracture for long bones were specified with clear definitions presented. A longitudinal fracture ias one that ias oriented roughly parallel to the long axis, while a transverse fracture runs at roughly right angles to the long axis. An oblique fracture runs roughly 45° to the long axis while a spiral is considered longer than an oblique fracture. The

fracture types noted in this study are transverse, oblique, and spiral. Longitudinal fractures were recorded as present or absent and were not used to identify the overall fracture. Fractures were classified according to the rough measurement of the angle of the fracture to the long axis of the shaft. Measurement of the distance between the most superior and most inferior parts of the fracture surface was used as a measurement of length (after Gifford-Gonzalez 1989a). Using a protractor, angle classes were transferred to graph paper (Figure 7), including 70 to 90 degrees, 45 to 70 degrees, and less than 45 degrees. The bone was aligned along the X-axis with the most superior portion of the fractured surface touching the Y-axis. An idealized line was then visualized from this point to the most inferior portion of the fracture in order to determine the angle of the fracture to the long axis. A spiral fracture would thus be one whose angle was determined to be less than 45 degrees while an oblique was considered 45 through 70 degrees. A transverse fracture was designated as 70 to 90 degrees. These divisions between transverse and oblique were arbitrarily chosen by the author since although overall orientation of a fracture may, for example, approach 90 degrees to the long axis, a pure transverse fracture will not be present. This is due simply to jagged edges. If a longitudinal fracture were present, the angle was determined from the most superior and inferior portions not connected with the longitudinal fracture. If not, any such fracture would always be considered a spiral fracture, albeit a most extreme form, since it would be 0° to the long axis, hence less than 45°.

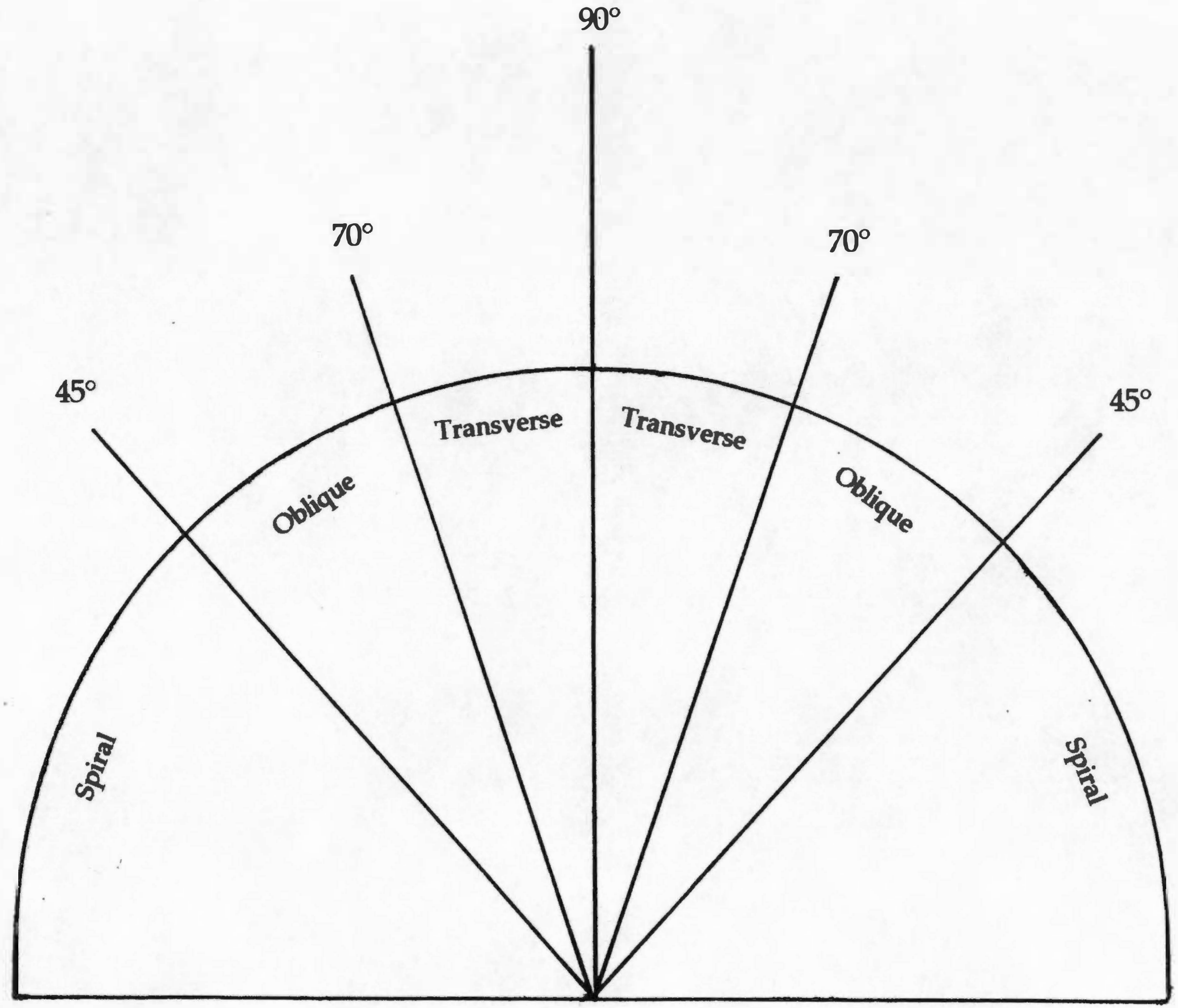

Figure 7: Angle classes for fracture classification.

Fractures which split the diaphyseal plates were also recorded. This is a phenomenon that was not observed in Bonnichsen's work with fresh bone (Bonnichsen 1979), but did occasionally appear in fresh specimens when a different breakage technique than his was used (Woltanski 1990). It also appears more frequently in boiled bone (Woltanski 1990).

Fracture surface texture was scored along a continuum ranging from 0 to 5. Fracture surfaces in fresh bone are generally regarded as smooth (Bonnichsen 1979) but boiled bone displays a rough, layered appearance (Woltanski 1990). For this score, the bone was regarded as an idealized square with anterior, posterior, medial and lateral aspects composing the four sides. A score of 0 was given to a smooth fracture surface, while scores of 1 and 2 were given to bone displaying hinge fractures of the cortical bone. A score of 1 corresponded to hinge fractures present on 1-2 sides and a score of 2 was given to a bone that displayed such fractures on 3-4 sides. Similarly, scores of 3 and 4 were given to bones that displayed splitting or layering of the bone surface. Again, the former score was applied to bones displaying such phenomena on 1-2 sides, and the latter score when bones showed this characteristic for 3-4 sides. A score of 5 was given if both hinge fractures and splitting was displayed.

For shaft fragments, only the surface texture, and the presence and appearance of an impact site were noted. No fragments smaller in length than 30 millimeters (mm) were analyzed. The scores for each series of observations for each group were submitted to

statistical analysis.

STATISTICAL ANALYSIS

The scores of the macroscopic analysis of the hand-fractured bones were first separated into two groups, either proximal or distal. The smaller fragments were not statistically analyzed because not all variables had been recorded. Proximal and distal groupings were analyzed separately, not because of an expectation that they would behave independently of each other, but because examining the two groups together would incorrectly increase the degrees of freedom. These groups were subjected to chi-square analysis. These tests determine the independence of impact, fracture classification, presence or absence of longitudinal fractures, continuation of fractures through diaphyseal plates, and surface texture from the treatment (fresh, boiled, or roasted) for both distal and proximal ends of all 90 bones. These tests examine the independence of the variables (Schlotzhauer and Littell 1987) but do not indicate the strength of the relationship (Kennedy 1983). For this reason, standardized residuals and Freeman-Tukey deviates were computed for these tables. Residuals are the differences between the observed and expected frequencies in contingency tables. The Freeman-Tukey deviates or variance stabilizing trasformations, should, for the most part, agree with the residuals. This agreement becomes closer as the sample size gets larger (Kennedy 1983). These residuals and Freeman-Tukey deviates functioned as z-scores for which two-tail

probabilities were then computed. Significance was assessed at the .05 level.

The maximum loads to failure for each group in the mechanical tests were subjected to an ANOVA procedure to determine if such loads were significantly different between fresh, roasted, and boiled bone. A separate ANOVA was performed on subsets of the boiled group. Also, a Kruskal-Wallis test, a nonparametric analogue to the ANOVA (Schlotzhauer and Littell 1987), was performed on the average number of blows required to hand-fracture each group and on the average number of fragments per group. Again, a separate Kruskal-Wallis was performed on number of blows for subsets of the hand-fractured boiled group.

SCANNING ELECTRON MICROSCOPY

In addition, scanning electron microscopy was utilized in order to examine the morphology of the fractured surfaces. The use of the SEM in taphonomic studies is well-documented (Olsen 1988; Potts and Shipman 1981; Shipman 1981; Shipman et al. 1984), and has been used consistently as a diagnostic tool in biomechanical and engineering studies of bone (see Burr et al. 1988; Piekarski 1970; Pope and Outwater 1972; Swedlow 1975; Vose 1963). Bone specimens were cut with a Stryker bone saw from the fractured edge of bones from all three categories. Care was taken to ensure that specimens were cut from the same area of the bone as well as making sure the fracture orientation was the same. For example, samples were taken from the

proximal third of both a fresh and boiled bone with fractures in both of these oriented obliquely. Nine experimental specimens were viewed on the Hitachi S-800 scanning electron microscope of the Zoology Department of the University of Tennessee.

These specimens were washed in acetone, mounted, and then sputter-coated with 8-10 nanometers (nm) of gold-palladium (AuPd) depending on the size of the specimen. The sputter-coater was equipped with a quartz-crystal monitor to check the thickness of the metal. At least 24 hours prior to viewing, all specimens were placed in the chromium coater, a sputter coater that lays down chromium instead of AuPd. The vacuum in the chromium coater is of better quality than that of the sputter coater and a brief stay in it generally eliminated problems with water vapor from the bone specimen discharging in the chamber of the microscope. Specimens were viewed at a 45° tilt using 4-6 Kilo-electron volts (KeV).

ARCHAEOLOGICAL APPLICATION

An actual blind test of method was not conducted but is being prepared. The current study was conducted in order to identify characteristics that would be helpful in identifying the predepositional state of bone, and determine the significance of those characters. The blind test will ask a researcher to examine treated bone and use those items determined to be significant in this study to place specimens in a treatment category.

However, several archaeological specimens were examined

with the SEM to determine the applicability of this aspect of the method to older bone. These faunal remains are from both an historic site and a site dating to the Archaic Period. A juvenile Sus scrofa proximal femur fragment was supplied by Dr. Charles H. Faulkner and Justin Lev-Tov from the Gibbs house faunal material. The Gibbs house is an historic site (40KN124) in East Knox county. The house was built in 1792 according to family lore (Faulkner 1988), and still stands today. The bone fragment was excavated on 11 August 1990 during the fourth field season at the house. Two specimens were taken for microscopy as described above.

A specimen for SEM analysis was also taken from a shaft fragment of a white-tailed deer (Odocoileus virginianus), provided by Drs. Walter F. Klippel and Darcy F. Morey. This fragment was excavcated from the Hayes site (40ML139), an extensive multicomponent site that largely consists of a Middle Archaic shell midden (Klippel and Morey 1986). This site is located in Marshall County, Tennessee, near the Duck River.

CONCLUSION

In an effort to identify the differences between pretreated and fresh bone, two types of testing were done. Mechanical testing was performed on a number of bones. These included fresh, boiled, and roasted bones. The same types of bone were also fractured by hand, then observed macroscopically. Several specimens were viewed with the SEM.

CHAPTER 5

RESULTS AND DISCUSSION

The results of this study, although not entirely definite, provide a firm starting point for further research elucidating the differences between fresh bone and bone that has been subjected to heat through boiling or roasting. Preceeding a discussion and analysis are the results of the stress testing and the experimental hand fracturing. A discussion of a future test of method concludes the chapter. A final summary and questions to be asked of further research follows in Chapter 6.

RESULTS

One half of the total sample of suid femora was fractured using an Instron stress testing machine from the Engineering Department at the University of Tennessee, Knoxville. These bones were used solely for the purpose of determining the relative strengths of the groups involved and their fracture patterns were not examined macroscopically nor microscopically. The maximum load to failure was recorded as well as the behavior of the bones during the fracturing process. These latter observations include sound, reaction of the bone to fracture, as well as general load-deformation curve shape. It is found that fresh bone sounds different than boiled bone during breakage, and the reaction of fresh bone to fracture is more

violent than that of boiled bone. Roasted bone reacts in much the same way as fresh bone but with a precipitous drop in strength. Observations of the general shape of the load-deformation curves between the three groups show a swift climb through the elastic region with very little plastic phase for fresh bone, and residual strength spikes and a longer plastic phase for boiled bone. The load-deformation curves for the roasted samples look much like those of fresh bone, but with a slightly longer climb through the elastic region. A change in behavior was observed for the final 19 of the boiled bone sample. This group of bones displays a significant drop in strength from the first 11, as well as a change in sound and performance. The maximum loads to failure for each group were subjected to an ANOVA procedure to determine if such loads were significantly different between fresh, roasted, and boiled bone. Results of the procedure indicate that while roasted bone can bear loads that are significantly less than that of fresh and boiled bone, surprisingly enough these latter two groups are not significantly different at the $p=.05$ level.

The results of the macroscopic analysis of the hand-fractured bones were subjected to chi-square analysis. These tables computed treatment by impact, fracture classification, presence or absence of longitudinal fractures, continuation of fractures through diaphyseal plates, and texture for both distal and proximal ends of all 90 bones. The majority of these tables show significance suggesting dependence between variables. Standardized residuals and Freeman-Tukey deviates were computed for these tables. Of 108 cell frequencies

computed, 26 show significant differences from the expected under the hypothesis of independence. In the distal portions, these include: the frequency of impact score 0 for boiled bone, the frequency of impact score 4 for boiled bone, the frequency of impact score 0 in roasted bone, the frequency of the spiral class in boiled bone, the frequency of the oblique class in fresh bone, the frequency of the spiral class in fresh bone, the frequency of the transverse class in fresh bone, the frequency of longitudinal fractures in boiled bone, the frequency of longitudinal fractures in fresh bone, the frequency of texture score 0 for boiled bone, and the frequency of texture score 3 for boiled bone. The proximal portions show significant values in the following areas: the frequency of impact score 4 for boiled bone, the frequency of impact score 4 for fresh bone, the frequency of the oblique class in fresh bone, the frequency of the spiral class in fresh bone, the frequency of the transverse class in fresh bone, the frequency of longitudinal fractures in boiled bone, the frequency of longitudinal fractures in fresh bone, the frequency of fractures continuing through the diaphyseal plate in fresh bone, the frequency of texture score 0 for boiled bone, the frequency of texture score 1 for boiled bone, the frequency of texture score 3 for boiled bone, the frequency of texture score 5 for boiled bone, the frequency of texture score 0 for fresh bone, the frequency of texture score 1 in roasted bone, and the frequency of texture score 5 in roasted bone. A Kruskal-Wallis test, a nonparametric analogue to the ANOVA (Schlotzhauer and Littell 1987), was performed on the average number of blows required to hand-fracture each group and on the

average number of fragments per group. The number of blows per bone varies significantly with the treatment group. The number of fragments per group does not vary significantly between fresh, boiled, and roasted bone. No difference is noted between subsets of boiled bone broken by hand.

Tentative results from the analysis of the micromorphology of the fractured surface using SEM are very promising, and provide ideas for further research. Unfortunately, only nine experimental specimens (F-24, F-26, F-10, B-2, B-7, B-1, R-28, R-11, R-21) were viewed due to time constraints. Three archaeological specimens were also viewed (G-1, G-2, H-1). Fresh bone samples display fibrous transverse orientation, with microscopic structures clearly visible. Boiled bone has an amorphous surface quality with microscopic structures less clearly visualized. Individual osteonal pullout may be present. Roasted specimens show roughened surfaces with visualization of microscopic structures being little to none. Some degree of osteonal pullout may be present. Archaeological specimens show an amorphous surface, no visualization of microscopic features, and no osteonal pullout.

DISCUSSION

During machine fracturing of the elements, several subjective observations were made about the reactions of the various groups involved. Fresh bone tends to break with a sharp snapping sound, and "jumps" slightly on the supports. Fractures travel completely

through the diaphysis but bones generally do not fall completely apart due to the presence of the periosteum. Boiled bone does not snap; failure is accompanied by a crunching, splintery noise. Rarely do fractures cut completely through the diaphysis, but are most often a single linear crack. The Instron is devised to unload a specimen at first failure. First failure for most boiled specimens did not include complete through-and-through fracture. If the Instron had pressed until complete fracture, load levels for the boiled specimens may have been significantly higher. Roasted bone behaves much as fresh bone does, breaking with a sharp snap and jump. The largest difference seen between fresh and roasted is the strength.

Several interesting changes to the above generalizations appear roughly midway through the boiled bone sample. After the 11th element was fractured, there was a drop in strength for the boiled elements. At this point in the experiment, the bones had been out of the boiling water for roughly 1 hour and 20 minutes and were cool to the touch. Some of the femora continued to splinter; however, more began to snap like fresh bone. Three of the bones not only broke with a snap, but fractured completely through and proceeded to fly through the air to separate corners of the room. The mean load of the first 11 femora was 1175 pounds (lbs.) while for the remaining 19, the mean load borne was 828 lbs. A t-test (see Appendix B1) was performed on the means, and the difference is significant (p-value<<.001). The behavior of the first 11 bones is consistent with what other researchers have observed. Sedlin (1965) notes an increase in bending strain in bone that was kept hydrated in solution

following boiling although he did not examine strength differences. Amprino (1958) observes an increase in microhardness for heated bone. The only explanation I can offer should be considered highly tentative. Collagen is water-soluble (Garrett and Flory 1956). Although grease may be lost through boiling, the bone itself remains hydrated. This hydration may help to increase the ductility of the material. As the material cools (i.e. the remaining 19 bones), water is given off into the air. It has been shown that strength of bone declines with higher temperatures (Bonfield and Li 1966). Thus once the elements are no longer fully hydrated, they are weakened. A study exists comparing tensile and compressive strengths for samples of hydrated bone (Bargren et al. 1974); and several can be found comparing hydrated samples to dehydrated samples. One such study (Amprino 1958) examines only microhardness and shows an increase in same for dried bone. It also documents an eventual increase in brittleness with temperature. Another study (Sedlin 1965) notes a considerable difference between the load-deformation curves of wet and dry bone.

Some general comments about the shape of the load-deformation curves should also be made. Examples of the curves from the three sample groups can be seen in Figure 8. A swift climb through the elastic region with very little plastic phase can be seen for fresh bone. Boiled bone shows a longer elastic and plastic phase. Small spikes are present on the majority of the return sides for the boiled bone. These are residual strength spikes (A. Mathews, personal communication 1992). They represent the strength left in

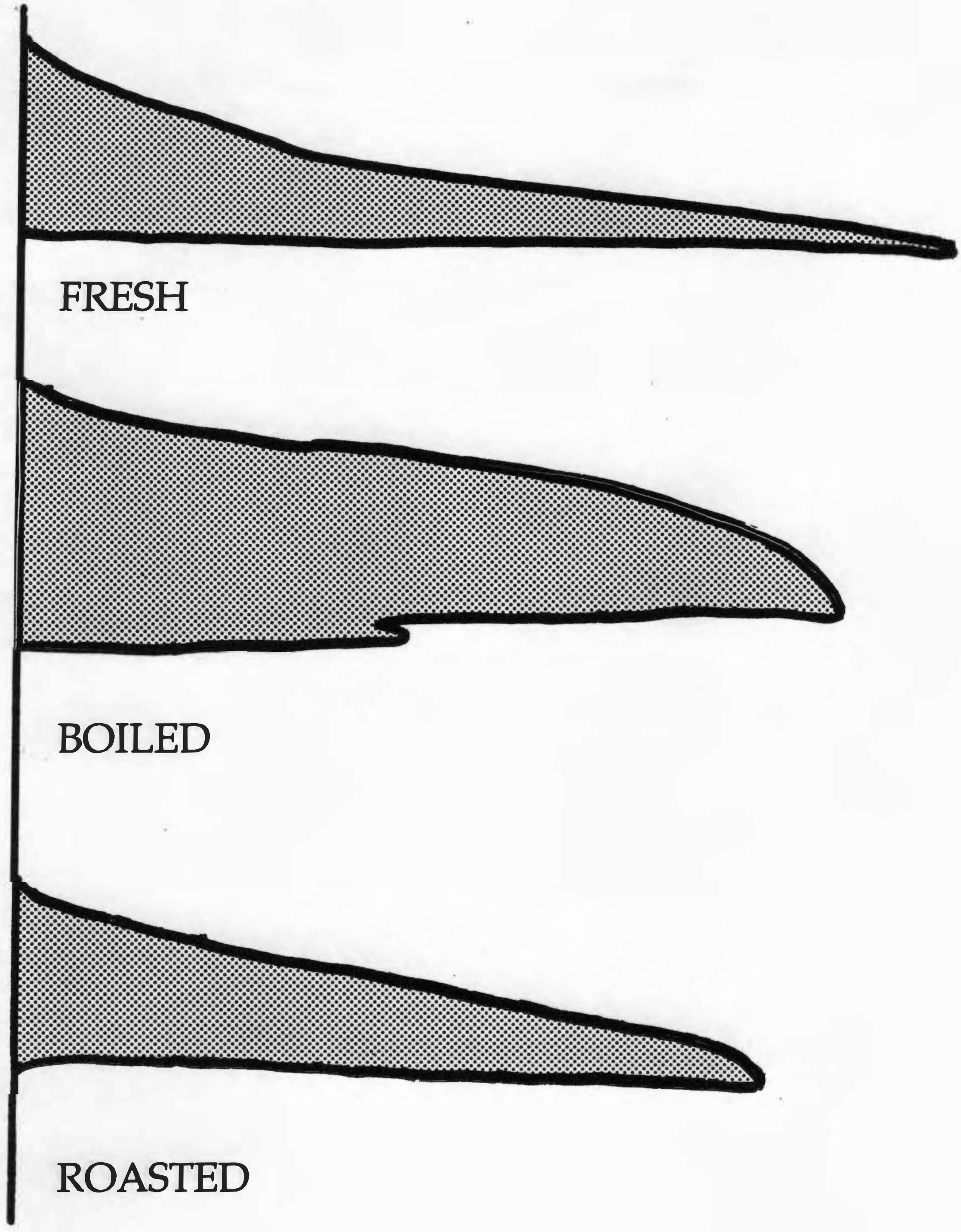

Figure 8: Examples of load-deformation curves for the three experimental groups.

the bone. Recall that most of the boiled bones did not fracture completely through. The load-deformation curves for the roasted samples look much like those of fresh bone, but with a slightly slower climb through the elastic region. Although strain was not directly measured in this experiment, a rough idea of the strain may be obtained from the curve itself. By observing the length between the start of the curve to the return line, a rough idea of the time spent in deformation is available (A. Mathews, personal communication 1992). It is seen that boiled and roasted bones exhibit greater length, suggesting greater deformation. These curves illustrate some of the behaviors described above. Fresh bone ascends to a certain load and then fractures quickly. Boiled bone deforms more and does not break all the way through. Roasted bone deforms more than fresh but fractures all the way through.

The maximum loads to failure for each group were also subjected to an ANOVA procedure (See Appendix B2) to determine if such loads are significantly different between fresh, roasted, and boiled bone. Based on a sample of 30 each, the mean total load borne by fresh bone is 1048, with a maximum load of 1590 lbs. and a minimum of 720 lbs. For boiled bone, the mean is 955 lbs (maximum=1450 lbs., minimum=470 lbs.), while the roasted bone bears a mean of 780 lbs (maximum=1230 lbs., minimum=290 lbs.). At the p=.05 significance level, boiled bone and fresh bone did not display significant differences. The load carried by roasted bone is significantly less than the other two. If boiled bone had not displayed a drop in strength following cooling, or if the Instron had loaded

boiled specimens through complete fracture, results for the fresh and boiled specimens may have been more in line with those of William Whitehead (personal communication 1992).

The results of the macroscopic analysis of the hand-fractured bones were subjected to a chi-square goodness of fit test. These tests examine the hypothesis of independence for the row and column data (Schlotzhauer and Littell 1987). All tables were computed (see Appendix B3-B12 where the sum of the squared z's=chi^2 distributed) for treatment (i.e. fresh, boiled, or roasted) by the other variables, including impact, fracture classification, presence or absence of longitudinal fractures, continuation of fractures through diaphyseal plates, and texture for both distal and proximal ends of all 90 bones. All test statistics were significant (p=.05 or less) indicating non-independence, with the exception of the table for the distal ends checking treatment and the continuation of fractures through the diaphyseal ends, and for the proximal end testing treatment and impact. Standardized residuals and Freeman-Tukey deviates were also computed for these tables in order to define the relationship of the variables. Of 108 cell frequencies computed, 26 were significantly different from the expected frequencies under independence (see Appendix B for complete data (B3-B12) and scores (B13)).

In the distal portions significance is seen for the frequency of impact score 0 (p=.02 for standardized residual and p=.007 for Freeman-Tukey deviate) and score 4 (p=.008 standardized residual and p=.025 for Freeman-Tukey) for boiled bone. The score 0 means that no impact site is seen while score 4 represents a crush fracture as

impact. Five boiled bones display no sign of an impact point, while 13.33 are the expected value under the hypothesis of independence. In comparison, 15 bones show crush fractures while only 7.67 are expected. The greater number of crush fractures can be easily explained. Boiled bone is much harder to break by hand than other types. It is not surprising that the great number of blows required to break it leave their mark in some way. According to Amprino (1958), bone heated to 200° C. shows a slight tendency under indenting loads to crush. This also explains the fewer number of bones displaying no sign of impact. Impact score 4 is significant for boiled bone in the proximal sections also. This significance is only represented in the calculation for the Freeman-Tukey deviate (p=.04). Six bones are observed to have crush fractures while only 2.67 are expected.

Significance is displayed using the standardized residual only (p=.03) for the frequency of impact score 0 in the distal portions of roasted bone. Twenty-one bones show no sign of impact while 13.33 are expected. This may be due to the brittleness of roasted bone which snapped fairly easily when broken with a hammerstone. Some signs of impact may have been removed as small fragments which were not examined.

No fresh proximal bones show crush fractures as impact points, although 2.67 are expected. This is significant for the Freeman-Tukey deviate only (p=.015). Fresh bone can be loosely viewed as being somewhere in the middle of roasted and boiled bone in this aspect. Although not quite as brittle and quick to snap as roasted bone, it does not need the pounding of boiled bone. Thus, no crush fractures

are present.

The expected number of spiral fractures in the boiled treatment group is 15.67, however, 24 are observed in the distal grouping. This is significant for the standardized residual only ($p=.03$). The frequency for all three fracture classes are significant for fresh bone. For fresh bone 20 oblique fractures are observed while 10 are expected ($p=.0016$, $p=.008$). Fifteen spiral are expected for fresh bone; only one is observed ($p<<0.001$, $p<<0.001$). Lastly, 9 transverse specimens are seen while only 4.33 are expected. This is significant for the standardized residual only ($p=.02$). The same pattern is seen for the proximal grouping where 17 fresh bones exhibit oblique fractures where 8.67 are expected ($p=.0047$, $p=.016$). One spiral is observed although 15.67 are expected ($p<0.001$, $p<<0.001$) and 12 transverse are noted with 5.67 expected ($p=.0079$, $p=.027$). I do not wish, at this point, to attempt an explanation for each individual statistical test. However, it should be stressed that spiral fractures do not only appear in fresh bone nor is this the only fracture class present in this group. Davis (1985) concludes that contrary to most researchers, assemblages modified by hominids should contain fewer oblique (her term for spiral) fractures than most carnivore modified assemblages. This is supported by my data. Martens et al. (1986) discuss the transverse and oblique shaped fractures of whole frozen and then thawed femora subjected to bending. Spiral fractures are not mentioned. Various fracture classes can be seen in Figures 9 and 10.

Spiral fractures do occur in fresh bone; however, they also

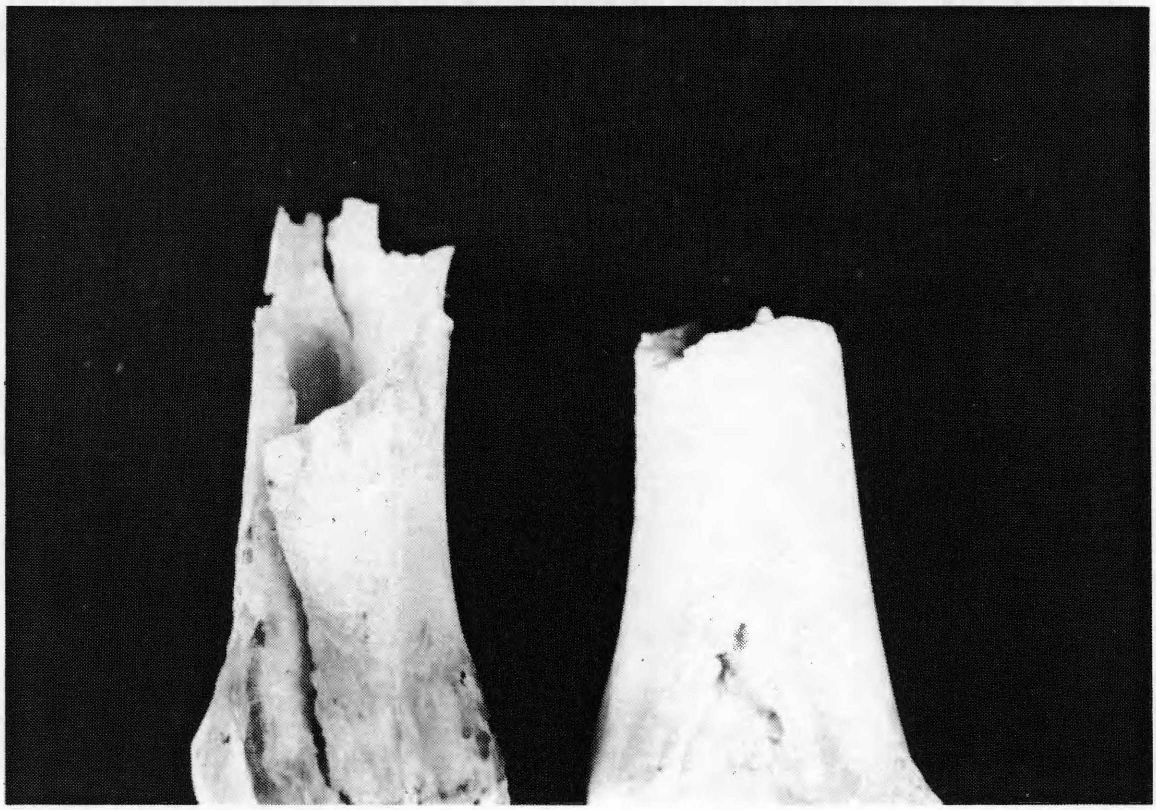

Figure 9: Experimentally hand-fractured fresh bone with transverse fracture and boiled bone with spiral fracture.
Fresh bone is on the right.

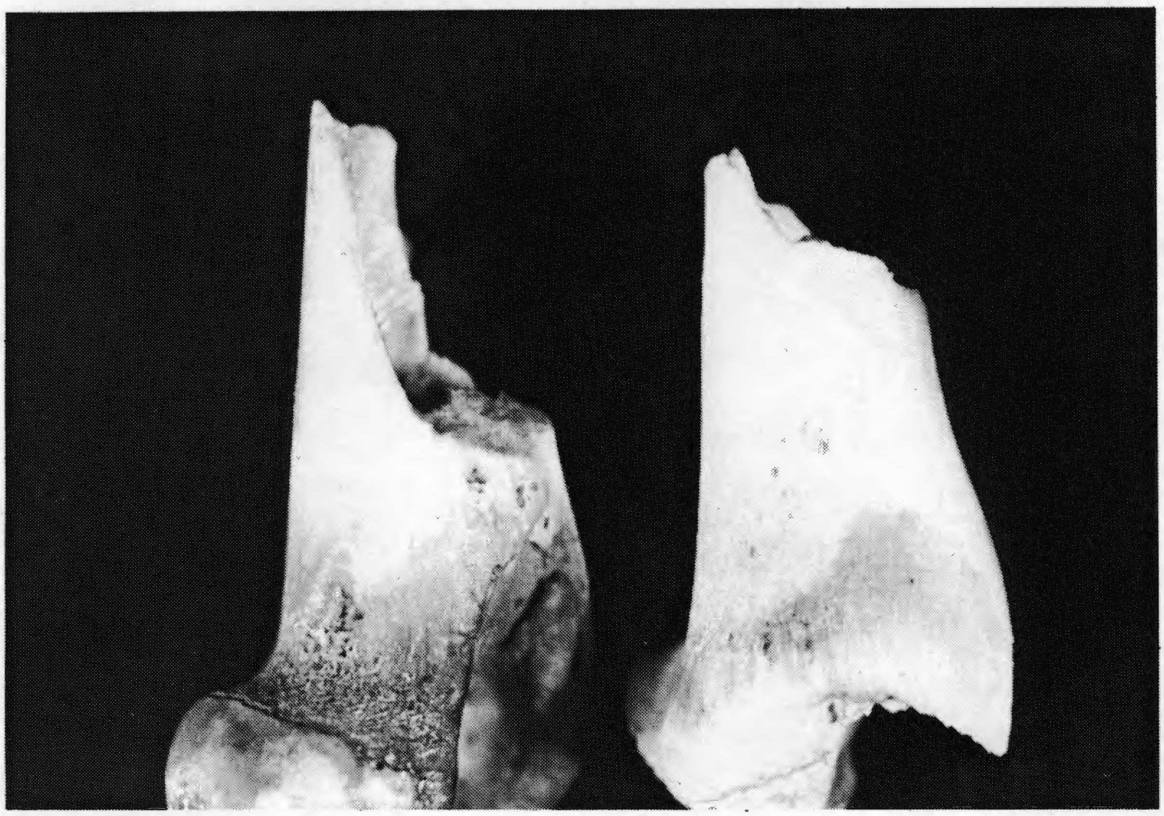

Plate 10: Experimentally hand-fractured fresh bone with oblique fracture and roasted bone with spiral fracture.
Fresh bone is on the right.

occur in culturally dried (i.e. boiled) bone. Blanket statements cannot be made about spiral fractures only appearing in fresh bone. Johnson (1985) is no doubt correct about the modes of fracture propagation being different for dried and fresh bone; however, when definitions for fracture types to be found in these two categories of bone overlap, differentiation between labels should not be attempted until a method can be presented to differentiate between fractures.

The presence of longitudinal fractures in both distal and proximal portions of the boiled experimental bones and the absence thereof in fresh bone show significant values. Boiled bone distal portions show 6 longitudinal fractures while 2.67 are expected. This is significant for the standardized residual only (p=.0416). Proximal portions show 8 with only 4 expected. Again, this is significant for the standardized residual only (p=.045). For fresh bone distal portions, the Freeman-Tukey deviate only shows significance (p=.015). No longitudinal fractures are seen although 2.67 are expected. The same pattern is seen for the proximal portions of fresh bone. None are seen although 4 are expected. This shows significance for both statistics (p=.045, p=.0018).

At this point, it should be remembered that split lines are small splits in bone whose placement is determined by the orientation of the collagen fibers (Ruangwit 1967); weathering cracks can be found in the same orientation as split-lines (Tappen 1969). Johnson (1985) notes a phenomena called split-line interference in dried bone, in which perpendicular or right angle offsets may be due to fractures crossing a bone until a split line is reached. The fracture travels down

the split line for a time, then jumps off. This phenomena is displayed in boiled bone (See Figure 11), a culturally dried material. Its absence in fresh bone should not be a surprise since split lines do not appear in this material unless artificially induced.

Texture scores for fractured surfaces of both distal and proximal portions show significance. In the distal portions, texture score 0, or smooth, appears for only 3 boiled bones, although it is expected in 12.33 bones under independence. Both test statistics show significance ($p=.0079$, $p<.0.001$). This is also the case for the proximal groupings. Five boiled bones are given this score, while 12 are expected. This also is significant for both test statistics ($p=.043$, $p=.02$). Two boiled bones in the proximal grouping show score 1, or hinge fractures present on 1-2 sides, while 7.33 are expected. Both computations show significance ($p=.049$, $p=.018$). Texture score 3, or splitting of bone tables on 1-2 sides, is significant for both proximal and distal boiled bones. In the distal grouping, 17 bones are given this score, while 10 is the expected frequency ($p=.027$, $p=.049$). Seventeen bones in the proximal group are also given this score, although only 8.33 are expected ($p=.0027$, $p=.0122$). Boiled bone in the proximal grouping also shows significance for the frequency of texture score 5, or both hinging and splitting displayed. Five bones display this phenomena, with only 2 being expected. This is significant for the standardized residual only ($p=.0339$).

Only the frequency of texture score 0 (smooth) for fresh bone shows significance. In the proximal grouping, 19 are observed while 12 are expected. Only the standardized residual displays significance

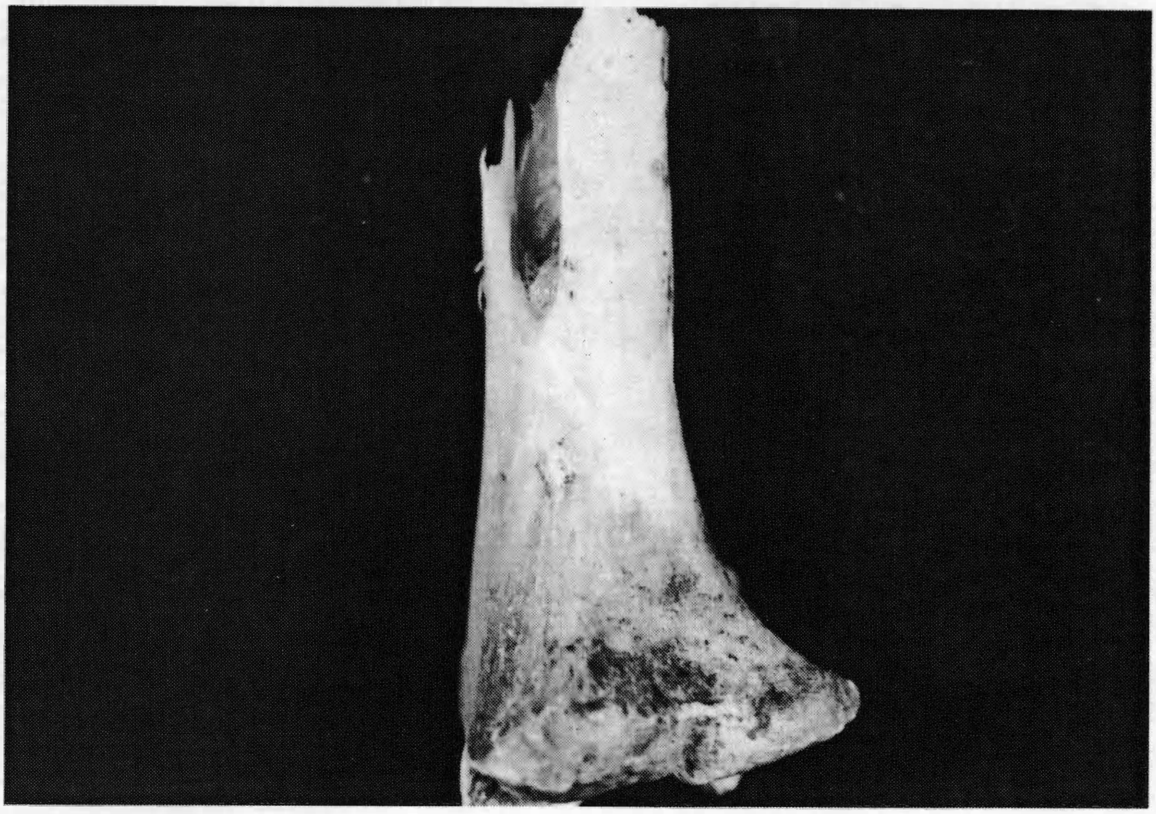

Figure 11: Experimentally hand-fractured boiled bone showing longitudinal fracture or split-line interference.

(p=.0433). For roasted bone, two scores display significance and both in the proximal grouping. These are score 1 (hinge fractures 1-2 sides) and score 5 (both hinging and splitting). For score 1, 14 are observed with only 7.33 expected. This shows significance for both test statistics (p=.0138, p=.035). No bones are assigned the score of five for roasted bone while 2 are expected. Only the Freeman-Tukey deviate shows this to be significant (p=.0455).

In other words, more boiled bones show rougher surfaces than expected, while fresh show more smooth surfaces than expected (See Figure 12). Roasted bones also tend to display smoother surfaces than expected. The results for the boiled bone and fresh bone support the observations of others. Morlan (1983) mentioning his own observations and those of others (Bonnichsen 1979) writes that fresh bone has a smooth surface texture while dried bone more often displays a rough texture. Boiled bone is more dry (i.e. less greasy) than fresh. In this case, this roughness may be due to the heavier pounding taken by boiled bone. This does not explain the tendency for roasted bone to display a smoother surface. It too is dry and so should be rougher. Then again, as noted in Chapter 3, brittle materials tend to break with a smooth surface. Roasted bone is certainly more brittle than boiled bone.

One more variable shows significant value. This is the frequency of fractures that continue through the diaphyseal plate in fresh bone for the proximal grouping. No bones display this feature although 5.67 are expected. This shows significance for both computations (p=.0173, p<.0.001). This result agrees with Bonnichsen

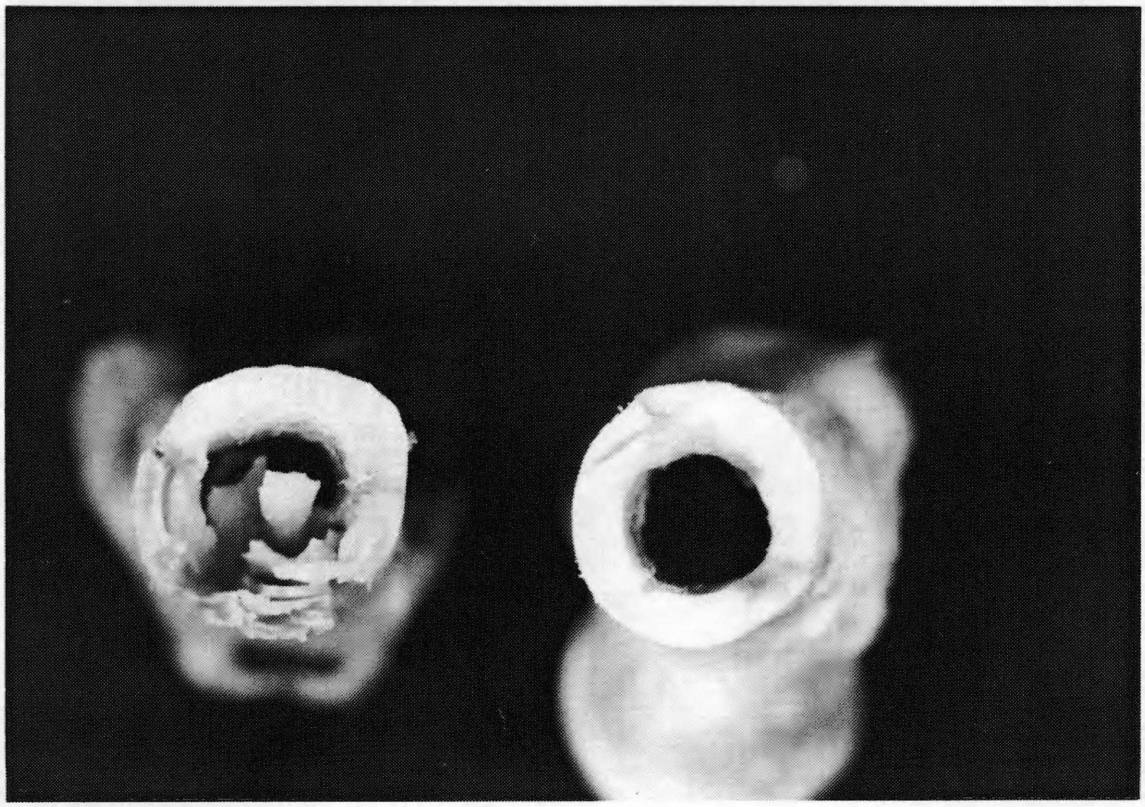

Figure 12: Typical textures for fresh and boiled bone.
The fresh bone is on the right.

(1979). This is not to say this phenomena does not happen. Two bones in the distal group display this feature (See Figure 13), although this is not significant.

A Kruskal-Wallis test, a nonparametric analogue to the ANOVA (Schlotzhauer and Littell 1987), was performed on the average number of blows required to hand-fracture each group (See Appendix B14). The average number of blows required to fracture fresh bone is 3.33; while for boiled, it is 20.9. Roasted bone needs an average of 4.13 blows to break. These are significant differences ($p<<0.001$). The first 15 boiled bones were broken while hot while the remainder were broken when cool to the touch. This was done in an effort to duplicate the results of the machine fracturing. However, no significant difference in number of blows is seen (Appendix B15).

The same test (See Appendix B16) was performed for the mean number of fragments per group. A mean of 3.63 fragments are present for fresh bone, with 4.83 present for boiled. Roasted bone shows the highest number of fragments with 5.9. The number of fragments per group does not vary significantly.

The original intent of the SEM analysis was to observe the path of the fracture through bone substance as a way to determine the pretreatment of bone. Shipman (1981) has used the SEM to observe the fracture path in spirally fractured weathered and fresh bone. She observes that fracture paths in fresh bone seem to cut through microscopic structures while in weathered bone, fractures propagate between such structures. However, due to inexperience dealing with microcracks and fracture propagation on the part of this researcher, it

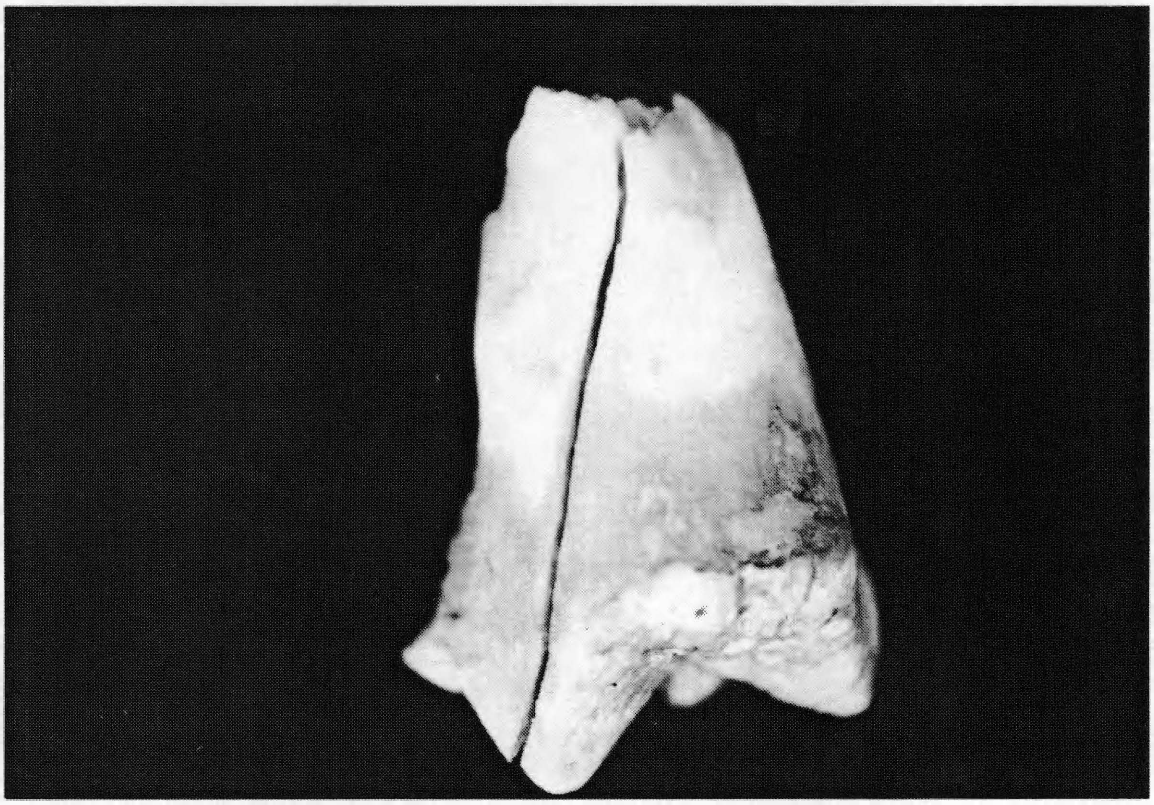

Figure 13: Fresh bone showing continuation of fracture through diaphyseal ends.

was found after viewing several specimens, surface morphology was a more reliable characteristic.

Observations of the micrograph taken of the fresh bone fracture surface reveal that although the surface is rough, the tiny collagen fibrils can be seen, and the bone exhibits a transverse organization (See Figure 14). Microscopic structures, such as Haversian canals and canaliculi, can be viewed without difficulty in fresh bone (See Figure 15). This should be contrasted with the appearance of the boiled fracture surface. In these micrographs (Figures 16 and 17), it can be seen that the surface exhibits an amorphous quality. There is little organization to the bone surface, except what is offered by the tiny blood vessel canals, or canaliculi, and the collagen fibers cannot be demonstrated. Roasted bone also displays a very rough surface with little to no organization. Microscopic structures cannot be demonstrated, or appear very rarely, in the micrographs of roasted bone (See Figures 18, 19, and 20). This amorphous nature is consistent with the behavior of heated collagen, which melts (Bonar and Glimcher 1970; Garrett and Flory 1956; Richter 1986). As mentioned, Bonar and Glimcher (1970) saw both the short-range (helical) and long-range ("the packing of collagen macromolecules in the characteristic staggered arrangement of native collagen fibrils" (Bonar and Glimcher 1970:545)) structure of collagen disrupted by heating. Short-range structure will be regained after cooling; however, long-range order in not fully mineralized bones is permanently lost if the temperature is high enough (i.e. roughly >5° above the temperature at which collagen shrinks). Collagen would

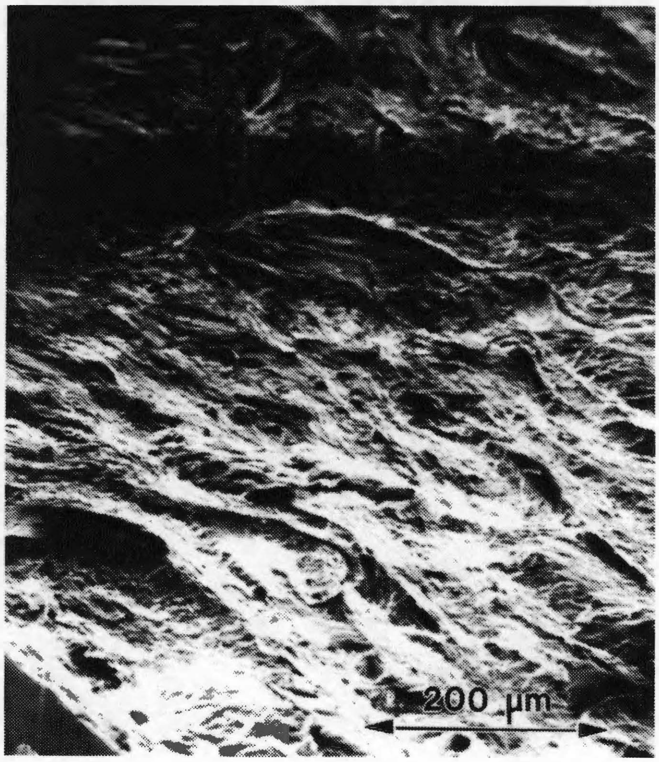

Figure 14: Specimen F-26 at 6 KeV on S-800 showing fibrous organization.

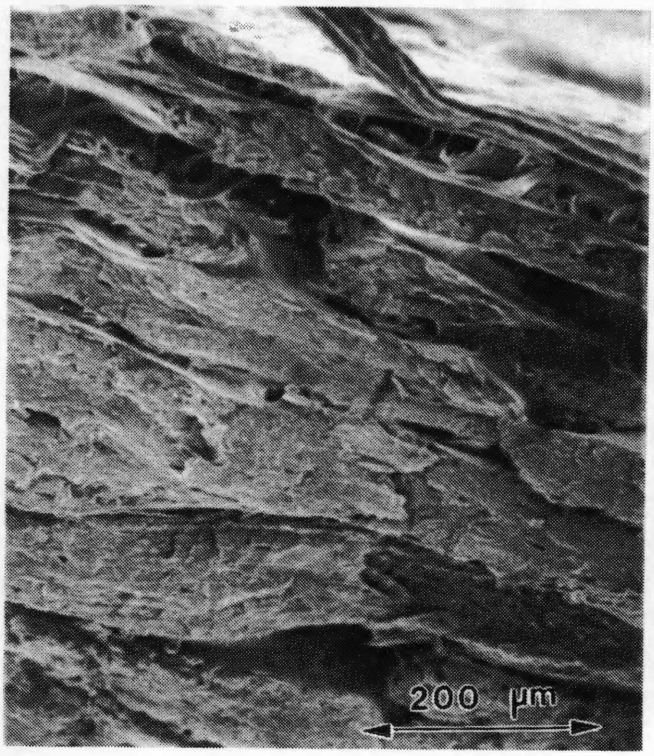

Figure 15: Specimen F-26 at 6 KeV on S-800 showing clearness of microscopic structures.

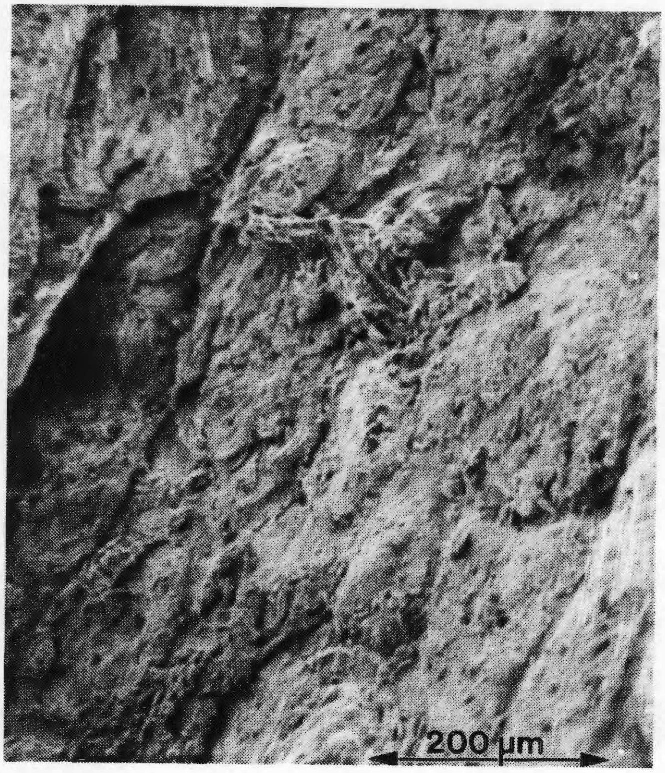

Figure 16: Specimen B-2 at 6 KeV on S-800 showing amorphous surface quality.

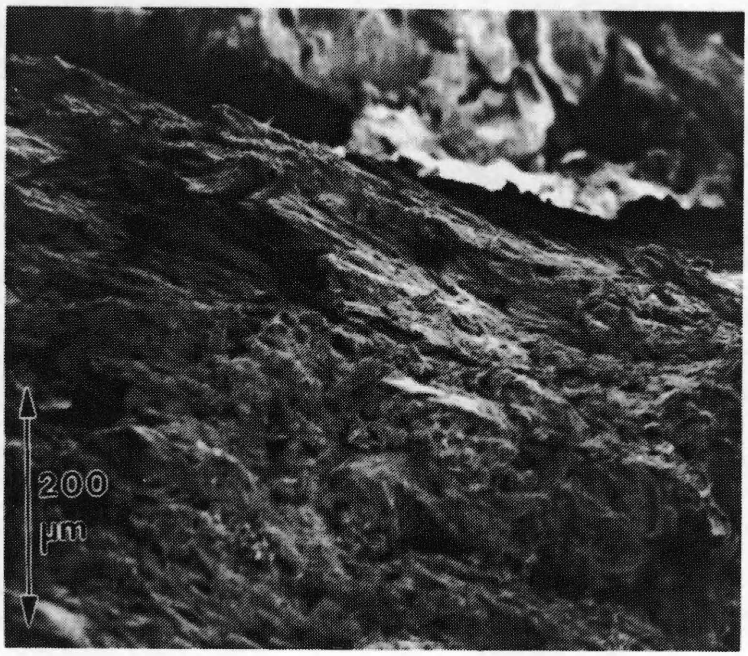

Figure 17: Specimen B-2 at 6 KeV on S-800 showing
less clear microscopic structures.

Figure 18: Specimen R-28 at 4 KeV on S-800
showing rough surface texture.

Figure 19: Specimen R-21 at 4 KeV on S-800 showing little to no surface organization and view of microscopic structures.

Figure 20: Specimen R-28 at 4 KeV on S-800 showing one microscopic structure. Note osteon in center left.

reform in its original state only if the heat were not enough to destroy the long order structure (Black 1989). Since collagen shrinkage temperatures generally are noted to be within the range of 54-62° C. (Bonar and Glimcher 1970), both the roasting and boiling procedures affect the long-range structure of the collagen. Collagen eventually leaches out of bone following extensive heating in water (Hare 1980).

Osteonal, or fibrous, pull-outs are noted along the edges of the boiled bone (See Figure 21), and to a much lesser degree, in the roasted bone (See Figure 22). These are not seen in fresh bone. Black (1989) also notes these in his roasted bone sample. This "pull-out failure" (Piekarski 1970:221) has been noted by other researchers (Piekarski 1970) and is caused when individual fibers are pulled from the surrounding bone matrix by shear failure. Piekarski (1970) describes this configuration for bone in which the fracture has propagated slowly. Rapid propagation leaves a rough rippled surface. A possible explanation for this is that boiled bone is tougher and more ductile. Thus, the initial fracture edge may propagate more slowly resulting in pull-out failure. Roasted bone has a longer elastic phase than fresh bone, and so, fractures in it, too, may propagate more slowly. Fractures in fresh bone presumably propagate rapidly, so fibrous pull-outs are not noted.

Archaeological specimens show an amorphous surface, little to no visualization of microscopic features, and no osteonal pullout. The surface of the specimen from the Gibbs House (See Figure 23) seems to be somewhere in the middle between roasted and boiled bone, while that from the Hayes site (See Figure 24) most closely

Figure 21: Specimen B-2 with osteonal pull-outs noted.

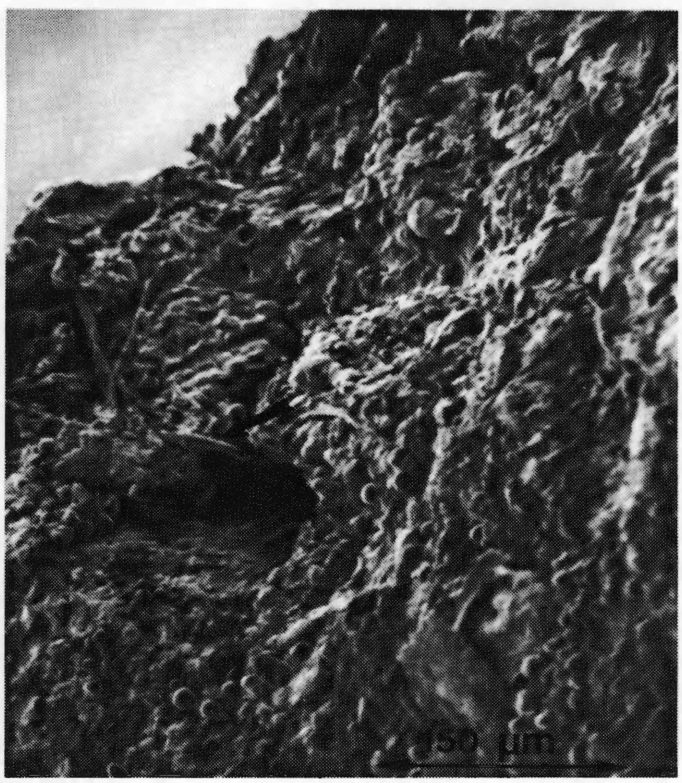

Figure 22: Specimen R-28 with fibrous pull-out noted.

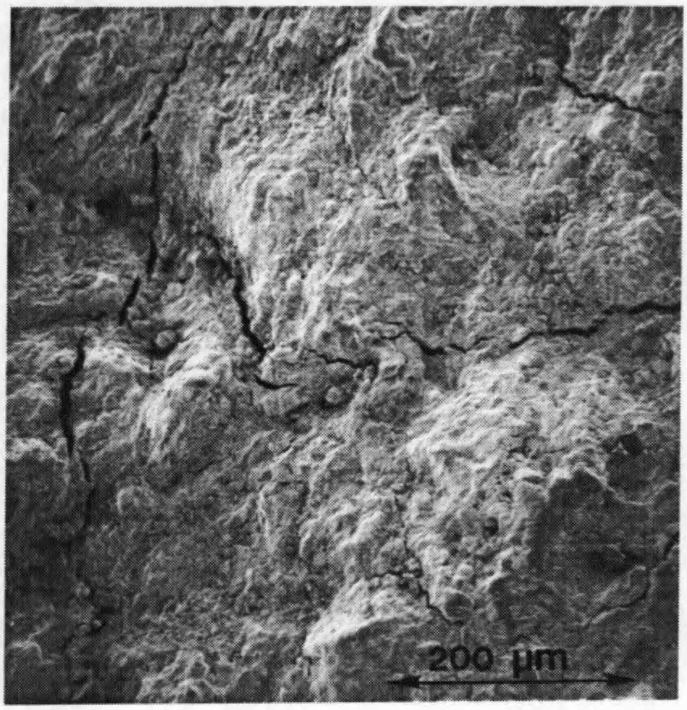

Figure 23: Specimen G-1 at 4 KeV on S-800 showing amorphous surface and faint traces of canaliculi. No osteonal pull-outs are seen.

Figure 24: Specimen H-1 at 4 KeV on S-800 showing roughened surface and no view of microscopic features. No fibrous pull-outs can be seen.

resembles that of roasted bone. In other words, faint traces of canaliculi can be seen in the Gibbs House specimen, but not in Hayes. However, due to the few specimens studied, this is merely speculation. Several post-depositional and diagenetic factors must be considered for archaeological specimens. No osteonal pull-outs are noted for these specimens; however, considering the fragility of such features, none should be expected. Richter (1986) notes that there are several types of bacteria and fungus that perform osteoclastic functions and destroy collagen fibrils. This may also explain the lack of surface detail.

TEST OF METHOD

An actual blind test of method was not conducted. One is planned for the near future and consists of examining bone that has been treated in various ways for those features shown to be significant. Based on these characters, it is hoped that experimental bone may be correctly assigned to its treatment class.

CONCLUSION

In conclusion, this study forms a basis for further research by identifying certain characteristics that are significantly related to treatment class. The actual behavior and strength of bones during fracture is important as is the number of blows required to hand-fracture an element. Boiled bone displays a rougher surface texture

and more signs of an impact point than both fresh and roasted bone. More oblique and transverse frractures than spiral were seen in fresh bone, while more spirals were seen in boiled bone. Longitudinal fractures are significant by their presence in boiled bone and by their absence in fresh bone. Fractures should not be expected to continue thruough diaphyseal plates in fresh bone but can.

SEM analysis shows a promisng start for determination of treatment through surface micromorphology. This method may be applied to older archaeological specimens after further research. At this point, it is suggested that using both macroscopic and microscopic approaches to this problem increases our knowledge of pretreated bone and is reccommended. Macroanalysis may be used alone while SEM analysis, prior to work with more samples, should be used in conjunction with the macroscopic approach.

CHAPTER 6

SUMMARY AND CONCLUSIONS

In this final chapter, I wish to summarize this thesis. The significance of the results will be discussed with attention to current research and interpretation of archaeological bone. Ideas for further research are suggested.

SUMMARY

In this actualistic work, three areas were studied with regards to cooked bone and its identification through its fracture pattern. The first consisted of mechanical testing of 90 Sus scrofa femora. Thirty of the bones were left fresh; 30 were boiled; and 30 were roasted. This sample was then subjected to three-point loading by an Instron stress testing machine in order to determine how treatment is related to strength. The loads to failure were recorded and found to be significant. Observations were made concerning the reactions of the bones to fracture and the shapes of the accompanying load-deformation curves.

In the second part of the study, another 90 bones, divided as before, were hand-fractured by the author. The bones were placed upon two supports and a hammerstone was used to strike the middle of the bone until fracture was complete. Macroscopic analysis was performed with various features proving to be significant. These

included surface texture, fracture class, the presence of longitudinal fractures, and the continuation of fractures through diaphyseal ends.

Specimens of bone were examined using the SEM and although results are tentative, they are promising. Changes in surface texture and ability to view microscopic structures form a possible basis for the assignment of bone to its treatment class. Examination of archaeological bone showed its appearance to be most consistent with that of treated bone; however, post-depositional and diagenetic factors must be taken into account before classifying an archaeological specimen with regard to pretreatment.

SIGNIFICANCE FOR CURRENT RESEARCH AND INTERPRETATIONS

This study was made in an attempt to increase the cultural inferences that could be made from the archaeological record. The ability to determine the method of food preparation for various sites would greatly increase the interpretation of past lifeways.

One area impacted by the study is that of current knowledge of fresh and dry bone fracture. For example, Figure 25 shows a shortened bone category criteria chart from the current literature (Johnson 1985:Table 5.2). All items in italics are items affected by this study. These items need further research.

In addition, the study forms a basis for further work on the problem of pre-or-post incineration trauma for human skeletal remains, whether archaeological or forensic in origin.

Bone Category Criteria	
Fresh	1. *Radial pattern circling around the diaphysis*
	2. Smooth fracture surface
	3. Homogeneous color from exterior cortical surface to compact bone
	4. Obtuse and acute angles formed by fracture and cortical surfaces
	5. *Loading point present*
	6. *Fracture fronts never crosscut epiphyseal ends*
Dry and Mineralized	1. *Perpendicular to horizontal single fracture surface cutting across long axis of diaphysis*
	2. Rough fracture surface
	3. Homogeneous or heterogeneous color
	4. Right angles formed by fracture and cortical surface
	5. *Loading point absent*
	6. Fracture front can crosscut epiphyseal end
Cultural Dynamic Loading	1. *Impact point/ rebound point*
	2. *Helical pattern at 45° angle to longitudinal axis*
	3. Size of impact
	4. Stress relief fracture surface features
	5. Redundant patterned flaking
	6. Tooth markings absent

Figure 25: Bone Category Criteria. Those items in italics need refinement. Modified from Johnson (1985:Table 5.2).

IDEAS FOR FURTHER RESEARCH

This thesis also suggests many ideas for further research. Chief among them are the following:

--How does cortical bone thickness affect fracture class? As an individual ages, cortical thickness changes. Will this affect the way fractures propagate through the bone?

--How does periosteum removal affect fracture class? It is suggested (Bonnichsen1973) that the periosteum was removed prior to fracture. Without this protective structure, the fracture produced may be different as well as the effort required to fracture the element. Are a portion of the differences noted between boiled/roasted bone and fresh bone merely due to the absence of this sheath?

--Does age of specimen involved affect fracture type? My study utilized only immature specimens. For instance, would fractures that travel through the diaphyseal plate in immature bone actually cut through the epiphysis in mature specimens? Would a line of fusion act as a deterrent?

--Does freezing alter fracture class? I used fresh bones; other researchers (Bonnichsen 1973; Johnson 1985) used thawed frozen bone. Our results are different. Prehistoric peoples probably were not modifying frozen bone. We must be careful about applying such experimental results.

--How does bacteria or other natural processes alter the microscopic appearance of archaeological bone? Osteoclastic bacteria are said to destroy collagen fibers (Richter 1986). Would weathered bone appear

similar to culturally dried bone?

--How does method of breakage alter appearance? I used only one. In a previous study (Woltanski 1990), differences were noted.

--How does element type affect the process? I used only femora but the humerus is reported to have a higher ultimate tensile strength (Lindahl and Lindgren 1967). Would this affect fracture class or simply breakage strategy?

--What differences can be seen in fracture patterns for bones loaded rapidly (by hand) vs. bones loaded statically (by Instron)?

--Can it be determined if a bone was broken, then cooked; or cooked, then broken? Yellen (1991) notes a preference for pre- or post-cooking fracturing based on species.

These are questions for further research. A blind test of method for my study will also help to determine the practical application of treated bone's significant features.

CONCLUSIONS

In conclusion, although this study is preliminary, it does point out several significant observations about the cultural modification of bone. It also suggests promising areas for further research on the subject of cooked bone and its identification in the archaeological record.

This problem must be approached with an open mind. Johnson (1985) did an admirable job with her review of bone technology. However, at least one problem with a review of this nature is that a

majority of its readers will interpret its contents as the law governing bone response. I personally feel that bone, as a biological material, is subject to the same idiosyncrasies of other biological specimens. It responds within certain parameters and as researchers, we should attempt to define these parameters. Others (e.g. Amprino 1958) have noted the large variation that can be found with bone. We, as anthropologists. should realize that it is too narrow a scope to believe that bone response can be defined with a yes or no list.

The biomechanical characteristics of bone must be considered as we attempt to interpret modification in the archaeological record. Heat alteration, in the form of cooking, affects the strength of the element and its micromorphology.

Mechanical testing during this study indicates that boiled and fresh bone can carry similar loads to first failure, although that failure is most often complete fracture for fresh bone and only a linear fracture for boiled bone. Roasted bone shows a significant drop in strength as compared to the other two groups. The strength of boiled bone declines significantly with cooling.

Macroscopic analysis shows several features that are significant. First, impact point and its degree of manifestation varies with treatment. Boiled bone shows signs of impact more than would be expected under a hypothesis of independence. This impact point often manifests itself as a crush fracture. Roasted bone rarely displays a impact point, while impact points in fresh bone are present, but not as crush fractures.

Fracture classes for some treatment groups were found to be

dependent upon treatment. The frequency of spiral fractures in boiled bone is greater than expected, while in fresh bone, the frequency is less than expected. The occurrence of both oblique and transverse fractures in fresh bone is more frequent than expected.

The presence of longitudinal fractures in the boiled experimental bones and the absence thereof in fresh bone show significant values.

Textures of fractured surfaces are also related to treatment. The macroscopic fracture surface for boiled bone is rarely smooth, and usually displays splitting or layering of the surface, with some hinge fractures also occurring. Fresh bone usually displays a smooth fracture surface. Roasted bone displays a smoother surface than expected. Some hinge fractures are seen in roasted bone, while splitting and hinging together are not evident in the sample.

One more feature shows significant value. This is the frequency of fractures that continue through the diaphyseal plate in fresh bone. This characteristic appears far less than expected, although this is not to say that it does not occasionally occur.

In addition, the number of blows required to hand-fracture the experimental bones varies significantly from fresh to boiled to roasted. The difference that can be seen with stress testing for hot and cool boiled bones does not manifest itself in the number of blows required to fracture the element.

Micrographs taken of the hand-fractured elements indicate differences in surface morphology and the ability to view microscopic structures. Fresh bone displays surface organization and structures

are highly visible. Boiled bone displays an amorphous surface with few visible microscopic structures. Roasted bone shows a very roughened surface with microscopic structures nearly invisible. Osteonal and fibrous pull-outs can be seen in boiled and roasted specimens.

Examination of archaeological specimens show an amorphous surface with little to no view of microscopic structures, and no osteonal pullouts. The historic specimen from the Gibbs House displays a morphology that combines characteristics seen in both boiled and roasted bone while the specimen from the Hayes site resembles roasted bone.

Although results are tentative, they are promising. Macroscopic features such as texture, fracture class, impact point, presence of longitudinal fractures, and fractures that continue through the diaphyseal ends are not independent of pretreatment and should be noted during analysis. Changes in microscopic surface texture and the ability to view associated structures form a possible basis for the assignment of bone to its treatment class. Knowledge of the mechanical characteristics of bone and how it is affected by treatment make it easier to determine choices available to past groups concerning ease of marrow extraction and bone modification. Prior to the advancement of a method to determine the treatment class of bone, however, post-depositional and diagenetic factors, such as bacterial infestation (Richter 1986) and leaching of collagen (Hare 1980), must be taken into account.

REFERENCES CITED

REFERENCES CITED

Agenbroad, L.D.

1989 Spiral Fractured Mammoth Bone from Nonhuman Taphonomic Processes at Hot Springs Mammoth Site. In *Bone Modification*, edited by R. Bonnichsen and M. Sorg, pp. 139-147. Center for the Study of the First Americans, Orono.

Amprino, R.

1958 Investigations on Some Physical Properties of Bone Tissue. *Acta Anatomica* 34:161-186.

Amtmann, E.

1968 The Distribution of Breaking Strength in the Human Femur Shaft. *Journal of Biomechanics* 1:271-277.

Armstrong, R.W., B. Arkayin, and G. Haddad

1971 Fracture of Bone Materials in Compression at Temperatures between -200° C and +200° C. *Nature* 232:576-577.

Ascenzi, A., P. Baschieri, and A. Benvenuti

1990 The Bending Properties of Single Osteons. *Journal of Biomechanics* 23:763-771.

Ascenzi, A., A. Benvenuti, and E. Bonucci

1982 The Tensile Properties of Single Osteonic Lamellae: Technical Problems and Preliminary Results. *Journal of Biomechanics* 15:29-37.

Ascenzi, A., and E. Bonucci

1964 The Ultimate Tensile Strength of Single Osteons. *Acta Anatomica* 58:160-183.

Baraibar, M.A., and P. Schoning

1985 Effects of Freezing and Frozen Storage on Histological Characteristics of Canine Tissues. *Journal of Forensic Sciences* 30:439-447.

Bargren, J.H., C.A.L. Bassett, and A. Gjelsvik

1974 Mechanical Properties of Hydrated Cortical Bone. *Journal of Biomechanics* 7:239-245.

Behrensmeyer, A.K.

1978 Taphonomic and Ecologic Information from Bone Weathering. *Paleobiology* 4:150-162.

Belanger, L.F.

1969 Osteocytic Osteolysis. *Calcified Tissue Research* 4:1-12.

Betts-Symonds, G.W.

1984 *Fracture: Care and Management for Students*. Macmillan Publishers LTD, London.

Binford, L.R.

1978 *Nunamiut Ethnoarchaeology*. Academic Press, New York.

1981 *Bones: Ancient Men and Modern Myths*. Academic Press, New York.

Black, A.T.

1989 *The Effects of Cooking on the Fracture Pattern of Bovine Bone: A Microstructural Study*. Unpublished Master's thesis, Department of Anthropology, State University of New York, Binghamton.

Bonar, L.C., and M.J. Glimcher

1970 Thermal Denaturation of Mineralized and Demineralized Bone Collagens. *Journal of Ultrastructure Research* 32:545-551.

Bonfield, W., and P.K. Datta

1974 Young's Modulus of Compact Bone. *Journal of Biomechanics* 7:147-149.

Bonfield, W. and C.H. Li

1966 Deformation and Fracture of Bone. *Journal of Applied Physics* 37:869-875.

Bonnichsen, R.

1973 Some Operational Aspects of Human and Animal Bone Alteration. In *Mammalian Osteo-Archaeology: North America*, edited by B.M. Gilbert, pp. 9-24. Missouri Archaeological Society, Missouri.

1979 *Pleistocene Bone Technology in the Beringian Refugium.* Ottawa: National Museum of Man Mercury Series Paper No. 89, Archaeological Survey of Canada, Ottawa.

Bonnichsen, R. and R. Will

1980 Cultural Modification of Bone: The Experimental Approach in Faunal Analysis. In *Mammalian Osteology*, edited by B.M. Gilbert, pp. 7-30. Laramie, Wyoming.

Boyde, A.

1972 Scanning Electron Microscope Studies of Bone. In *The Biochemistry and Physiology of Bone, Volume 1, Second Edition*, edited by G. H. Bourne, pp. 259-309. Academic Press, New York.

Brain, C.K.

1981 *The Hunters or the Hunted?: An Introduction to African Cave Taphonomy*. University of Chicago Press, Chicago.

Bunn, H.T.

1981 Archaeological Evidence for Meat-Eating by Plio-Pleistocene Hominids from Koobi Fora and Olduvai Gorge. *Nature* 291:574-577.

1989 Diagnosing Plio-Pleistocene Hominid Activity with Bone Fracture Evidence. In *Bone Modification,* edited by R. Bonnichsen and M. Sorg, pp. 299-315. Center for the Study of the First Americans, Orono.

Bunn, H. T. and E. M. Kroll

1986 Systematic Butchery by Plio/Pleistocene Hominids at Olduvai Gorge, Tanzania. *Current Anthropology* 27:431-452.

Burr, D.B., M.B. Schaffler, and R.G. Frederickson

1988 Composition of the Cement Line and Its Possible Mechanical Role as a Local Interface in Human Compact Bone. *Journal of Biomechanics* 21:939-945.

Burr, D.B., R.B. Martin, M.B. Schaffler, and E.L. Radin

1985 Bone Remodeling in Response to *in vivo* Fatigue Microdamage. *Journal of Biomechanics* 3:189-200.

Burstein, A.H., J.D. Currey, V.H. Frankel, and D.T. Reilly
1972 The Ultimate Properties of Bone Tissue: The Effects of Yielding. *Journal of Biomechanics* 5:35-44.

Caler, W.E., and D.R. Carter
1989 Bone Creep-Fatigue Damage Accumulation. *Journal of Biomechanics* 22:625-635.

Carter, D.
1992 Personal Communication. Lay's Packing Co., Inc., Knoxville.

Carter, D.R.
1987 Mechanical Loading History and Skeletal Biology. *Journal of Biomechanics* 20:1095-1109.

Carter, D.R., and W.C. Hayes
1977 Compact Bone Fatigue Damage--I. Residual Strength and Stiffness. *Journal of Biomechanics* 10:325-337.

Carter, D.R. and D.M. Spengler
1982 Biomechanics of Fracture. In *Bone in Clinical Orthopaedics: A Study in Comparative Osteology*, edited by G. Sumner-Smith, pp. 305-334. W.B. Saunders Company, Toronto.

Clark, J.G.D., and M.W. Thompson

1953 The Groove and Splinter Technique of Working Antler in Upper Paleolithic and Mesolithic Europe. *Proceedings of the Prehistoric Society* 19:148-160.

Currey, J.D.

1959 Differences in the Tensile Strength of Bone of Different Histological Types. *Journal of Anatomy* 93:87-95.

1964 Three Analogies to Explain the Mechanical Properties of Bone. *Biorheology* 2:1-10.

1984 *The Mechanical Adaptations of Bones*. Princeton University Press, Princeton.

1988 The Effect of Porosity and Mineral Content on the Young's Modulus of Elasticity of Compact Bone. *Journal of Biomechanics* 21:131-139.

Dart, R.

1959 Adventures with the Missing Link. Harper & Brothers Publishers, New York.

Davis, K.L.

1985 *A Taphonomic Approach to Experimental Bone Fracturing and Applications to Several South African Pleistocene Sites.* Unpublished Ph.D. dissertation. Department of Anthropology, State University of New York, Binghamton.

DeKleer, V.S.

1982 Development of Bone. In *Bone in Clinical Orthopaedics: A Study in Comparative Osteology*, edited by G. Sumner-Smith, pp. 1-80. W.B. Saunders Company, Philadelphia.

Evans, F.G.

1978 Relations Between Torsion Properties and Histology of Adult Human Compact Bone. *Journal of Biomechanics* 11:157-165.

Evans, F.G., and M. Lebow

1952 Regional Differences in Some of the Physical Properties of the Human Femur. *American Journal of Surgery* 83:326-331.

Evans, F.G., and R. Vincentelli

1974 Relations of the Compressive Properties of Human Cortical Bone to Histological Structure and Calcification. *Journal of Biomechanics* 7:1-10.

Faulkner, C.H.

1988 *Archaeological Testing at the Nicholas Gibbs House: Season I.* Submitted to the Nicholas Gibbs Historical Society. Department of Anthropology, University of Tennessee, Knoxville.

Fawcett, D.W.

1986 *Bloom and Fawcett: A Textbook of Histology, Eleventh Edition*. W.B. Saunders Company, Philadelphia.

Frost, H.M.

1967 *An Introduction to Biomechanics.* C.C. Thomas, Springfield.

Garrett, R.R., and P.J. Flory

1956 Evidence for a Reversible First-Order Phase Transition in Collagen-Diluent Mixtures. *Nature* 177:176-177.

Gifford-Gonzalez, D.

1989a Ethnographic Analogues for Interpreting Modified Bones: Some Cases from East Africa. In *Bone Modification*, edited by R. Bonnichsen and M. Sorg, pp. 179-246. Center for the Study of the First Americans, Orono.

1989b Modern Analogues: Developing an Interpretive Framework. In *Bone Modification*, edited by R. Bonnichsen and M. Sorg, pp. 43-52. Center for the Study of the First Americans, Orono.

Gilbert, B.M.
1990 *Mammalian Osteology, Third Edition*. Missouri Archaeological Society, Columbia.

Gilchrist, R., and H.C. Mytum
1986 Experimental Archaeology and Burnt Animal Bone from Archaeological Sites. *Circaea, The Bulletin of the Association for Environmental Archaeology* 4:29-38.

Haglund, W.D., D.T. Reay, and D.R. Swindler
1988 Tooth Mark Artifacts and Survival of Bones in Animal Scavenged Human Skeletons. *Journal of Forensic Sciences* 33:985-997.

Hancox, N.M.
1972 The Osteoclast. In *The Biochemistry and Physiology of Bone, Second Edition, Volume 1*, edited by G.H. Bourne, pp. 45-66. Academic Press, New York.

Hare, P.E.
1980 Organic Geochemistry of Bone and Its Relation to the Survival of Bone in the Natural Environment. In *Fossils in the Making: Vertebrate Taphonomy and Paleoecology*, edited by A.K. Behrensmeyer and A.P. Hill, pp. 208-219. The University of Chicago Press, Chicago.

Haynes, G.
1983 Frequencies of Spiral and Green-Bone Fractures on Ungulate Limb Bones in Modern Surface Assemblages. *American Antiquity* 48:102-114.

Hill, A.
1989 Bone Modification by Modern Spotted Hyenas. In *Bone Modification*, edited by R. Bonnichsen and M. Sorg, pp. 169-178. Center for the Study of the First Americans, Orono.

Hirsch, C., and O. Da Silva
1967 The Effect of Orientation on Some Mechanical Properties of Femoral Cortical Bone. *Acta Orthopaedica Scandinavica* 38:45-56.

Horwitz, V.D.
1987 *Description of Fracture Characteristics in Cooked and Fresh Bone.* Transcript of paper presented at the 52nd meeting of the Society for American Archaeology, Toronto, Canada.

Johnson, E.

1982 Paleo-Indian Bone Expediency Tools: Lubbock Lake and Bonfire Shelter. *Canadian Journal of Anthropology* 2:145-157.

1985 Current Developments in Bone Technology. In *Advances in Archaeological Method and Theory, Volume 8,* edited by M.S. Schiffer, pp. 157-235. Academic Press, New York.

Kennedy, J.J.

1983 *Analyzing Qualitative Data.* Praeger, New York.

Kent, S.

1984 *Analyzing Activity Areas: An Ethnoarchaeological Study of the Use of Space.* Unversity of New Mexico Press, Albuquerque.

Klippel, W.E. and D.F. Morey

1986 Contextual and Nutritional Analysis of Freshwater Gastropods from Middle Archaic Deposits at the Hayes Site, Middle Tennessee. *American Antiquity* 51:799-813.

Lakes, R.S., S. Nakamura, J.C. Behiri, and W. Bonfield

1990 Fracture Mechanics of Bone with Short Cracks. *Journal of Biomechanics* 23:967-975.

Lanyon, L.E.

1987 Functional Strain in Bone Tissue as an Objective, and Controlling Stimulus for Adaptive Bone Remodeling. *Journal of Biomechanics* 20:1083-1093.

Lanyon, L.E., and C.T. Rubin

1985 Functional Adaptation in Skeletal Structures. *Functional Vertebrate Morphology*, edited by M. Hildebrand, D.M. Bramble, K.F. Liem, and D.B. Wake, pp. 1-25. The Belknap Press, Cambridge.

Legros, R., N. Balmain, and G. Bonel

1987 Age-Related Changes in Mineral of Rat and Bovine Cortical Bone. *Calcified Tissue International* 41:137-144.

Lindahl, O., and A.G.H. Lindgren

1967 Cortical Bone in Man II. Variation in Tensile Strength with Age and Sex. *Acta Orthpaedica Scandinavica* 38:141-147.

Lyman, R.L.

1978 Prehistoric Butchering Techniques in the Lower Granite Reservoir, Southeastern Washington. *Tebiwa* 13:1-25.

Martens, M., R. Van Audekercke, P. De Meester, and J.C. Mulier

1986 Mechanical Behaviour of Femoral Bones in Bending Loading. *Journal of Biomechanics* 19:443-454.

Mather, B.S.

1968 Variation with Age and Sex in Strength of the Femur. *Medical and Biological Engineering* 6:129-132.

Mathews, A.

1992 Personal Communication. Engineering Department, University of Tennessee, Knoxville.

McLean, F.C., and M.R. Urist

1968 *Bone: Fundamentals of the Physiology of Skeletal Tissue*, Third Edition. The University of Chicago Press, Chicago.

Melick, R.A., and D.R. Miller

1966 Variations of Tensile Strength of Human Cortical Bone with Age. *Clinical Science* 30:243-248.

Miller, A., P. Rogers, and L. Haessly

1991 Serial Murder Aftershocks. *Newsweek* August CXVIII(7): 28-29.

Miller, G. J.

1975 A Study of Cuts, Grooves, and Other Marks on Recent and Fossil Bone: II Weathering Cracks, Fractures, Splinters, and Other Similar Natural Phenomena. In *Lithic Technology*, edited by E. Swanson, pp. 212-226. Mouton, The Hague.

Mjör, I.A.

1962 The Bone Matrix Adjacent to Cacunae and Canaliculi. *Anatomical Record* 144:327-339.

Morlan, R.E.

1983 Spiral Fractures on Limb Bones: Which Ones are Artificial? In *Carnivores, Human Scavengers & Predators: A Question of Bone Technology*, edited by G.M. LeMoine and A.S. MacEachern, pp. 241-269. Proceedings of the Fifteenth Annual Conference of the Archaeological Association of the University of Calgary, Calgary.

Newcomer, M.H.

1974 Study and Replication of Bone Tools from Ksar Akil (Lebanon). *World Archaeology* 6:138-153.

Nicholson, R.A.

1992 Bone Survival: the Effects of Sedimentary Abrasion and Trampling on Fresh and Cooked Bone. *International Journal of Osteoarchaeology* 2:79-90.

Noe-Nygaard, N.

1977 Butchering and Marrow Fracturing as a Taphonomic Factor in Archaeological Deposits. *Paleobiology* 3:218-237.

Nordin, M. and V.H. Frankel

1980 Biomechanics of Whole Bones and Bone Tissue. In *Basic Biomechanics of the Skeletal System*, edited by V.H. Frankel and M. Nordin, pp. 15-60. Lea & Febiger, Philadelphia.

Oliver, J.S.

1989 Analogues and Site Context: Bone Damages from Shield Trap Cave (24CB91), Carbon County, Montana, U.S.A.. In *Bone Modification*, edited by R. Bonnichsen and M. Sorg, pp. 73-98. Center for the Study of the First Americans, Orono.

Olsen, S.L.

1988 The Identification of Stone and Metal Tool Marks on Bone Artifacts. In *Scanning Electron Microscopy in Archaeology*, edited by S.L. Olsen, pp. 337-360. BAR International Series 452, Oxford.

Piekarski, K.

1970 Fracture of Bone. *Journal of Applied Physics* 41:215-223.

Pope, M.H. and J.O. Outwater

1972 The Fracture Characteristics of Bone Substance. *Journal of Biomechanics* 5:457-465.

1974 Mechanical Properties of Bone as a Function of Position and Orientation. *Journal of Biomechanics* 7:61-66.

Potts, R.B.

1984 Home Bases and Early Hominids. *American Scientist* 72:338-347.

Potts, R.B. and P. Shipman

1981 Cutmarks Made by Stone Tools on Bones from Olduvai Gorge, Tanzania. *Nature* 291:577-580.

Pritchard, J.J.

1972a General Histology of Bone. In *The Biochemistry and Physiology of Bone, Volume 1, Second Edition,* edited by G.H. Bourne, pp. 1-19. Academic Press, New York.

1972b The Osteoblast. In *The Biochemistry and Physiology of Bone, Volume 1, Second Edition,* edited by G.H. Bourne, pp. 21-40. Academic Press, New York.

Prud'homme, A.

1991 The Little Flat of Horrors. *Time* 138(5):126.

Ralston, E.L.

1967 *Handbook of Fractures.* The C.V. Mosby Company, St. Louis.

Reilly, D.T., A.H. Burstein, and V.H. Frankel

1974 The Elastic Modulus for Bone. *Journal of Biomechanics* 7:271-275.

Reitz, E.J.

1986 Urban/Rural Contrasts in Vertebrate Fauna from the Southern Atlantic Coastal Plain. *Historical Archaeology* 20:47-53.

Richter, J.

1986 Experimental Study of Heat Induced Morphological Changes in Fish Bone Collagen. *Journal of Archaeological Science* 13:477-481.

Robison, N.D.

1987 Zooarchaeology: Its History and Development. In *The Zooarchaeology of Eastern North America: History, Method and Theory, and Bibliography*, edited by A.E. Bogan and N.D. Robison, pp. 1-26. Miscellaneous Paper No. 12. Tennessee Anthropological Association , Knoxville.

Roesler, H.

1987 The History of Some Fundamental Concepts in Bone Biomechanics. *Journal of Biomechanics* 20:1025-1034.

Rogers, L.F.

1982 *Radiology of Skeletal Trauma*. Churchill Livingstone, New York.

Ruangwit, U.

1967 The Split-line Phenomenon and the Microscopic Structure of Bone. *American Journal of Physical Anthropology* 26:319-330.

Rubin, C.T.

1984 Skeletal Strain and the Functional Significance of Bone Architecture. *Calcified Tissue International* 36:S11-S18.

Sadek-Kooros, H.

1972 Primitive Bone Fracturing: A Method of Research. *American Antiquity* 37:369-382.

1975 Intentional Fracturing of Bone: Description of Criteria. In *Archaeozoological Studies*, edited by A.T. Clason, pp. 139-150. American Elsevier Publishing Company, New York.

Schaffler, M.B., and D.B. Burr

1988 Stiffness of Compact Bone: Effects of Porosity and Density. *Journal of Biomechanics* 21:13-16.

Schlotzhauer, S.D. and R.C. Littell

1987 *SAS System for Elementary Statistical Analysis*. SAS Institute, Inc., Cary.

Sedlin, E.D.

1965 A Rheologic Model for Cortical Bone. *Acta Orthopaedica Scandanavica*: Supplementum 83.

Sedlin, E.D., and C. Hirsch

1966 Factors Affecting the Determination of the Physical Properties of Femoral Cortical Bone. *Acta Orthpaedica* 37:29-48.

Semenov, S.A.

1964 *Prehistoric Technology*. Translated by M.W. Thompson. Barnes & Noble, Inc., London.

Shipman, P.

1981 Applications of Scanning Electron Microscopy to Taphonomic Problems. In The Research Potential of Anthropological Museum Collections, edited by A.M.E. Cantwell, J.B. Griffin, and N.A. Rothschild. *Annals of the New York Academy of Science* 376:357-385.

1984 Scavenger hunt. *Natural History* 4: 20-27.

Shipman, P., G. Foster, and M. Schoeninger

1984 Burnt Bones and Teeth: An Experimental Study of Color, Morphology, Crystal Structure and Shrinkage. *Journal of Archaeological Science* 11:307-325.

Simkin, A., and G. Robin

1974 Fracture Formation in Differing Collagen Fiber Pattern of Compact Bone. *Journal of Biomechanics* 7:183-188.

Simmons, D.J., N.B. Simmons, and J.H. Marshall

1970 The Uptake of Calcium-45 in the Acellular-Boned Toadfish. *Calcified Tissue Research* 5:206-221.

Smith, J.W.

1960 Collagen Fibre Patterns in Mamalian Bone. *Journal of Anatomy* 94:329-344.

Smith, E.L. and C. Gilligan

1989 Mechanical Forces and Bone. *Bone and Mineral Research* 6:139-173.

Sutcliffe, A.J.

1970 Spotted Hyaena: Crusher, Gnawer, Digester and Collector of Bones. *Nature* 227:1110-1113.

Swedlow, D.B.

1975 Scanning and Transmission Electron Microscopy of Calcified Tissues. *Biomaterials, Medical Devices, and Artifical Organs* 3:121-153.

Tappen, N.C.
1969 The Relationship of Weathering Cracks to Split-line Orientation in Bone. *American Journal of Physical Anthropology* 31:191-198.

Vaughan, J.
1981 *The Physiology of Bone, Third Edition.* Clarendon Press, London.

Vincentelli, R., and F.G. Evans
1971 Relations Among Mechanical Properties, Collagen Fibers, and Calcification in Adult Human Cortical Bone. *Journal of Biomechanics* 4:193-201.

Vose, G.P.
1963 Fine Structure of Bone as Seen on Fracture and Cleavage Planes by Electron Microscopy. *Anatomical Record* 145:183-191.

Vose, G.P., and D.J. Baylink
1970 Effect of Fibrillar Structure of Pericanalicular and Intercanalicular Bone on X-Ray Absorption. *Anatomical Record* 166:239-245.

Wall, J.C., S.K. Chatterji, and J.W. Jeffery
1979 Age-Related Changes in the Density and Tensile Strength of Human Femoral Cortical Bone. *Calcified Tissue International* 27:105-108.

Whitehead, W.
1992 Personal Communication. Department of Anthropology, Washington University.

Willey, P., and L.M. Snyder
1989 Canid Modification of Human Remains: Implications for Time-Since-Death Estimations. *Journal of Forensic Sciences* 34:894-901.

Wright, T.M., and W.C. Hayes
1977 Fracture Mechanics Parameters for Compact Bone--Effects of Density and Specimen Thickness. *Journal of Biomechanics* 10:419-430.

Woltanski, T.J.
1990 Intentional Fracturing of Bone: Determining the Extent of Hominid Modification. Ms. in possession of author. Department of Anthropology, University of Tennessee, Knoxville.

Yellen, J.E.
1991 Small Mammals: !Kung San Utilization and the Production of Faunal Assemblages. *Journal of Anthropological Archaeology* 10:1-26.

Yesner, D.R., and R. Bonnichsen
1979 Caribou Metapodial Shaft Splinter Technology. *Journal of Archaeological Science* 6:303-308.

Zierhut, N.W.
1967 Bone Breaking Activities of the Calling Lake Cree. *Alberta Anthropologist* 1:33-36.

APPENDICES

APPENDIX A

FRACTURE ANALYSIS

Date: ________________

Broken by: Woltanski

Pretreatment: ___Yes

___Boiled ___Roasted

Experiment No.: F___

B___

R___

Element: femur

Species: *Sus scrofa*

___No

____ **number of blows**

Breakage strategy: Bone was placed with epiphyseal ends on two separate supports, and a hammer stone was used to impact the anterior middle.

Number of fragments: ___________

Impact site: 0 1 2 3 4

0= No impact site seen

1= Impact seen as fragment removal

2= Concentric ring fractures seen

3= Impact site seen (concentric ring fractures, negative scars)

4= Impact site seen as crush fracture

Fracture classification:

____Transverse: Roughly right angle to bone (70-90°)

____Oblique: Roughly 45-70° to long axis

____Spiral Roughly <45°

Fracture lines split diaphyseal plates:

___yes ____no

Fracture surface texture:

0 1 2 3 4 5

0= smooth

1= Hinge fractures present on 1-2 sides

2= Hinge fractures present on 3-4 sides

3=Splitting of bone tables on 1-2 sides
4=Splitting of bone tables on 3-4 sides
5= Both hinging and splitting displayed

Notes:____
____
____
____
____
____

SEM Analysis: ____yes ____no

SEM Analysis

Date:______ Specimen # ______
Preparation:
____
____
____

Magnification:__________________________
Observations:
____
____
____
____
____
____
____

Micrographs: _____ yes ____no
_____ negatives ____Polaroids

____
____

APPENDIX B

DATA

T-Test Procedure

Variable: LBS

Type	N	Mean	Std. Dev.	Std. Error
a	11	1175.45454545	184.55967254	55.64683502
b	19	827.63157895	134.18859470	30.78497493

Variances	T	DF	Prob>/T/
Unequal	5.4694	16.2	0.0001
Equal	5.9583	28.0	0.0000

For HO: Variances are equal, F' = 1.89 DF = (10, 18)

Prob>F' = 0.2298

Appendix B1: Maximum loads to failure for boiled bone.

Analysis of Variance Procedure

T-tests (LSD) for variable: Force

Alpha=0.05 df=87 MSE=45350.37

Critical Value of T=1.99

Least Significant Difference=109.29

Means with the same letter are not significantly different.

T-grouping	Mean	N	type
A	1047.83	30	f
A	955.17	30	b
B	779.83	30	r

Appendix B2: Maximum loads to failure for all groups.

Treatment by Impact for Distal Portions

Score:	0	1	2	3	4
Boiled					
Observed	5	4	6	0	15
Expected	13.33	3.33	5.33	0.33	7.67
S.T.*	-2.2815	0.3672	0.2902	-0.5745	2.6467
F-T. D.*	-2.6847	0.4519	0.3708	-0.5232	2.2445
Fresh					
Observed	14	4	8	0	4
Expected	13.33	3.33	5.33	0.33	7.67
S.T.*	0.1835	0.3672	1.1565	-0.5745	-1.3252
F-T. D.*	0.2444	0.4519	1.1040	-0.5232	-1.3924
Roasted					
Observed	21	2	2	1	4
Expected	13.33	3.33	5.33	0.33	7.67
S.T.*	2.1008	-0.7288	-1.4424	1.1663	-1.3252
F-T. D.*	1.9028	-0.6379	-1.5781	0.8911	-1.3924

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B3: Frequency Table

Treatment by Fracture Class for Distal Portions

Class:	oblique	spiral	transverse
Boiled			
Observed	5	24	1
Expected	10	15.67	4.33
S.T.*	-1.5811	2.1043	-1.6003
F-T. D.*	-1.7176	1.9190	-1.866
Fresh			
Observed	20	1	9
Expected	10	15.67	4.33
S.T.*	3.1623	-3.7059	2.2443
F-T. D.*	2.6516	-5.5658	1.8821
Roasted			
Observed	5	22	3
Expected	10	15.67	4.33
S.T.*	-1.5811	1.5991	-0.6392
F-T. D.*	-1.7176	1.5063	-0.5481

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B4: Frequency Table

Treatment by Presence of Longitudinal Fractures for Distal Portions		
Presence/absence:	no	yes
Boiled		
Observed	24	6
Expected	27.33	2.67
S.T.*	-0.637	2.0379
F-T. D.*	-0.6044	1.6776
Fresh		
Observed	30	0
Expected	27.33	2.67
S.T.*	0.5107	-1.6340
F-T. D.*	0.5415	-2.4176
Roasted		
Observed	28	2
Expected	27.33	2.67
S.T.*	0.1282	-0.4100
F-T. D.*	0.1733	-0.2713

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B5: Frequency Table

Treatment by Continuation of Fractures through Diaphyseal Ends for Distal Portions

Continue:	no	yes
Boiled		
Observed	27	3
Expected	28	2
S.T.*	-0.189	0.7071
F-T. D.*	-0.1425	0.7321
Fresh		
Observed	28	2
Expected	28	2
S.T.*	0.0000	0.0000
F-T. D.*	0.0465	0.1463
Roasted		
Observed	29	1
Expected	28	2
S.T.*	0.189	-0.7071
F-T. D.*	0.2322	-0.5858

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B6: Frequency Table

Treatment by Texture for Distal Portions

Score:	0	1	2	3	4	5
Boiled						
Observed	3	4	0	17	1	5
Expected	12.33	5	0	10	0.33	2.33
S.T.*	-2.6571	-0.4472	0	2.2136	1.1663	1.7492
F-T. D.*	-3.3616	-0.3465	0	1.9626	0.8911	1.4731
Fresh						
Observed	17	5	0	7	0	1
Expected	12.33	5	0	10	0.33	2.33
S.T.*	1.33	0	0	-0.9487	-0.5746	-0.8713
F-T. D.*	1.2721	0.103	0	-0.9289	-0.5232	-0.7983
Roasted						
Observed	17	6	0	6	0	1
Expected	12.33	5	0	10	0.33	2.33
S.T.*	1.33	0.4472	0	-1.2649	-0.5746	-0.8713
F-T. D.*	1.2721	0.5127	0	-1.3079	-0.5232	-0.7983

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B7: Frequency Table

Treatment by Impact for Proximal Portions

Score:	0	1	2	3	4
Boiled					
Observed	14	4	5	1	6
Expected	19	3.67	3.67	1	2.67
S.T.*	-1.1471	0.1723	0.6443	0.0000	2.0379
F-T. D.*	-1.1603	0.2763	0.7258	0.1781	1.6776
Fresh					
Observed	21	5	3	1	0
Expected	19	3.67	3.67	1	2.67
S.T.*	0.4588	0.6943	-0.3497	0.0000	-1.6340
F-T. D.*	0.4980	0.7258	-0.2277	0.1781	-2.4176
Roasted					
Observed	22	2	3	1	2
Expected	19	3.67	3.67	1	2.67
S.T.*	0.6882	-0.8717	-0.3497	0.0000	-0.4100
F-T. D.*	0.7113	0.8135	-0.2429	0.1781	-0.2713

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B8: Frequency Table

Treatment by Fracture Class for Proximal Portions

Class:	oblique	spiral	transverse
Boiled			
Observed	5	23	2
Expected	8.67	15.67	5.67
S.T.*	-1.2464	1.8517	-1.5413
F-T. D.*	-1.2877	1.7148	-1.7199
Fresh			
Observed	17	1	12
Expected	8.67	15.67	5.67
S.T.*	2.8290	-3.7059	2.6584
F-T. D.*	2.3925	-5.5658	2.2034
Roasted			
Observed	4	23	3
Expected	8.67	15.67	5.67
S.T.*	-1.5860	1.8517	-1.1213
F-T. D.*	-1.7372	1.7148	-1.1342

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B9: Frequency Table

Treatment by Presence of Longitudinal Fractures for Proximal Portions		
Presence/absence:	no	yes
Boiled		
Observed	22	8
Expected	26	4
S.T.*	-0.7845	2
F-T. D.*	-0.7607	1.7053
Fresh		
Observed	30	0
Expected	26	4
S.T.*	0.7845	-2.0000
F-T. D.*	0.7980	-3.1231
Roasted		
Observed	26	4
Expected	26	4
S.T.*	0.0000	0.0000
F-T. D.*	0.0482	0.113

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B10: Frequency Table

Treatment by Continuation of Fractures through Diaphyseal Ends for Proximal Portions		
Continue:	no	yes
Boiled		
Observed	20	10
Expected	24.33	5.67
S.T.*	-0.8778	1.818
F-T. D.*	-0.8609	1.6127
Fresh		
Observed	30	0
Expected	24.33	5.67
S.T.*	1.1495	-2.3812
F-T. D.*	1.1293	-3.866
Roasted		
Observed	23	7
Expected	24.33	5.67
S.T.*	-0.0669	0.5585
F-T. D.*	-0.2208	-0.608

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B11: Frequency Table

Treatment by Texture for Proximal Portions

Score:	0	1	2	3	4	5
Boiled						
Observed	5	2	1	17	0	5
Expected	12	7.33	0.33	8.33	0	2
S.T.*	-2.0207	-1.9687	1.1663	3.004	0.0000	2.1213
F-T. D.*	-2.3144	-2.3601	0.8911	2.5074	0.0000	1.6856
Fresh						
Observed	19	6	0	4	0	1
Expected	12	7.33	0.33	8.33	0	2
S.T.*	2.0207	-0.4912	-0.5745	-1.5003	0.0000	-0.7071
F-T. D.*	1.8310	-0.4111	-0.5232	-1.8583	0.0000	-0.5858
Roasted						
Observed	12	14	0.0000	4	0	0
Expected	12	7.33	0.33	8.33	0	2
S.T.*	0.0000	2.4636	-0.5745	-1.5003	0.0000	-1.4142
F-T. D.*	0.0697	2.1083	-0.5232	-1.6223	0.0000	-2

*Standardized residual
* Freeman-Tukey Deviate
Sum of Squared Z's=chi^2 distributed

Appendix B12: Frequency Table

Appendix B13: Z-SCORES, AND PROBABILITIES FOR MACROANALYSIS DATA, DISTAL PORTIONS

First number in z-score column is the standardized residual, second is Freeman-Tukey deviate.

z score	prob.	description of variable
-2.2815	0.0225	Frequency of score 0 for impact
-2.6847	0.0073	in boiled bone
0.3672	0.7135	Frequency of score 1 for impact
0.4519	0.6513	in boiled bone
0.2902	0.7717	Frequency of score 2 for impact
0.3708	0.7108	in boiled bone
-0.5745	0.5656	Frequency of score 3 for impact
-0.5232	0.6008	in boiled bone
2.6467	2.2445	Frequency of score 4 for impact
2.2445	0.0248	in boiled bone
0.1835	0.8544	Frequency of score 0 for impact
0.2444	0.8069	in fresh bone
0.3672	0.7135	Frequency of score 1 for impact
0.4519	0.6513	in fresh bone
1.1565	0.2475	Frequency of score 2 for impact
1.1040	0.2696	in fresh bone
-0.5745	0.5656	Frequency of score 3 for impact
-0.5232	0.6008	in fresh bone
-1.3252	0.1851	Frequency of score 4 for impact
-1.3924	0.1638	in fresh bone
2.1008	0.0357`	Frequency of score 0 for impact
1.9028	0.0571	in roasted bone
-0.7288	0.4661	Frequency of score 1 for impact
-0.6379	0.5235	in roasted bone
-1.4424	0.1492	Frequency of score 2 for impact
-1.5781	0.1145	in roasted bone
1.1663	0.2435	Frequency of score 3 for impact
0.8911	0.3792	in roasted bone
-1.3252	0.1851	Frequency of score 4 for impact
-1.3924	0.1638	in roasted bone
-1.5811	0.1139	Frequency of oblique fracture class
-1.7176	0.0859	in boiled bone
2.1043	0.0354	Frequency of spiral fracture class
1.9190	0.0550	in boiled bone
-1.6003	0.1095	Frequency of transverse fracture class
-1.8666	0.0620	in boiled bone
3.1623	0.0016	Frequency of oblique fracture class
2.6516	0.0080	in fresh bone

-3.7059	0.0002	Frequency of spiral fracture class
-5.5658	0.0000	in fresh bone
2.2443	0.0248	Frequency of transverse fracture class
1.8821	0.0598	in fresh bone
-1.5811	0.1139	Frequency of oblique fracture class
-1.7176	0.0859	in roasted bone
1.5991	0.1098	Frequency of spiral fracture class
1.5063	0.1320	in roasted bone
-0.6392	0.5227	Frequency of transverse fracture class
-0.5481	0.5836	in roasted bone
-0.6370	0.5241	Absence of longitudinal fractures
-0.6044	0.5456	in boiled bone
2.0379	0.0416	Frequency of longitudinal fractures
1.6776	0.0934	in boiled bone
0.5107	0.6096	Absence of longitudinal fractures
0.5415	0.5882	in fresh bone
-1.6340	0.1023	Frequency of longitudinal fractures
-2.4176	0.0156	in fresh bone
0.1282	0.8980	Absence of longitudinal fractures
0.1733	0.8624	in roasted bone
-0.4100	0.6818	Frequency of longitudinal fractures
-0.2713	0.7862	in roasted bone
-0.1890	0.8501	Absence of fractures through diaphyseal plate
-0.1425	0.8867	in boiled bone
0.7071	0.4795	Frequency of fractures through diaphyseal plate
0.7321	0.4641	in boiled bone
0.0000	1.0000	Absence of fractures through diaphyseal plate
0.0465	0.9629	in fresh bone
0.0000	1.0000	Frequency of fractures through diaphyseal plate
0.1463	0.8837	in fresh bone
0.1890	0.8501	Absence of fractures through diaphyseal plate
0.2322	0.8164	in roasted bone
-0.7071	0.4795	Frequency of fractures through diaphyseal plate
-0.5858	035580	in roasted bone
-2.6571	0.0079	Frequency of score 0 for texture
-3.3616	0.0008	in boiled bone
-0.4472	0.6547	Frequency of score 1 for texture
-0.3465	0.7290	in boiled bone
0.0000	1.0000	Frequency of score 2 for texture
0.0000	1.0000	in boiled bone
2.2136	0.0269	Frequency of score 3 for texture
1.9626	0.0497	in boiled bone
1.1663	0.2435	Frequency of score 4 for texture
0.8911	0.3729	in boiled bone

1.7492	0.0803	Frequency of score 5 for texture
1.4731	0.1407	in boiled bone
1.3300	0.1835	Frequency of score 0 for texture
1.2721	0.2033	in fresh bone
0.0000	1.0000	Frequency of score 1 for texture
0.1030	0.9180	in fresh bone
0.0000	1.0000	Frequency of score 2 for texture
0.0000	1.0000	in fresh bone
-0.9487	0.3428	Frequency of score 3 for texture
-0.9289	0.3529	in fresh bone
-0.5746	0.5656	Frequency of score 4 for texture
-0.5232	0.6008	in fresh bone
-0.8713	0.3836	Frequency of score 5 for texture
-0.7983	0.4247	in fresh bone
1.3300	0.1835	Frequency of score 0 for texture
1.2721	0.2033	in roasted bone
0.4472	0.6547	Frequency of score 1 for texture
0.5127	0.6082	in roasted bone
0.0000	1.0000	Frequency of score 2 for texture
0.0000	1.0000	in roasted bone
-1.2649	0.2059	Frequency of score 3 for texture
-1.3079	0.1909	in roasted bone
-0.5746	0.5656	Frequency of score 4 for texture
-0.5232	0.6008	in roasted bone
-0.8713	0.3836	Frequency of score 5 for texture
-0.7983	0.4247	in roasted bone

Appendix B13: Z-SCORES, AND PROBABILITIES FOR MACROANALYSIS DATA, PROXIMAL PORTIONS

First number in z-score column is the standardized residual, second is Freeman-Tukey deviate.

z score	prob.	description of variable
-1.1471	0.2513	Frequency of score 0 for impact
-1.1603	0.2459	in boiled bone
0.1723	0.8632	Frequency of score 1 for impact
0.2763	0.7823	in boiled bone
0.6943	0.4875	Frequency of score 2 for impact
0.7258	0.4680	in boiled bone
0.0000	1.0000	Frequency of score 3 for impact
0.1781	0.8586	in boiled bone
2.0379	0.0416	Frequency of score 4 for impact
1.6776	0.0934	in boiled bone
0.4588	0.6464	Frequency of score 0 for impact
0.4980	0.6185	in fresh bone
0.6943	0.4875	Frequency of score 1 for impact
0.7258	0.4680	in fresh bone
-0.3497	0.7266	Frequency of score 2 for impact
-0.2277	0.8199	in fresh bone
0.0000	1.0000	Frequency of score 3 for impact
0.1781	0.8586	in fresh bone
-1.6340	0.1023	Frequency of score 4 for impact
-2.4176	0.0156	in fresh bone
0.6882	0.4913	Frequency of score 0 for impact
0.7113	0.4769	in roasted bone
-0.8717	0.3834	Frequency of score 1 for impact
-0.8135	0.4159	in roasted bone
-0.3497	0.7266	Frequency of score 2 for impact
-0.2429	0.8081	in roasted bone
0.0000	1.0000	Frequency of score 3 for impact
0.1781	0.8586	in roasted bone
-0.4100	0.6818	Frequency of score 4 for impact
-0.2713	0.7862	in roasted bone
-1.2464	0.2126	Frequency of oblique fracture class
-1.2877	0.1979	in boiled bone
1.8517	0.0641	Frequency of spiral fracture class
1.7148	0.0864	in boiled bone
-1.5413	0.1232	Frequency of transverse fracture class
-1.7199	0.0855	in boiled bone
2.8290	0.0047	Frequency of oblique fracture class
2.3925	0.0167	in fresh bone

-3.7059	0.0002	Frequency of spiral fracture class
-5.5658	0.0000	in fresh bone
2.6584	0.0079	Frequency of transverse fracture class
2.2034	0.0276	in fresh bone
-1.5860	0.1127	Frequency of oblique fracture class
-1.7372	0.0824	in roasted bone
1.8517	0.0641	Frequency of spiral fracture class
1.7148	0.0864	in roasted bone
-1.1213	0.2622	Frequency of transverse fracture class
-1.1342	0.2567	in roasted bone
-0.7845	0.4327	Absence of longitudinal fractures
-0.7607	0.4468	in boiled bone
2.0000	0.0455	Frequency of longitudinal fractures
1.7053	0.0881	in boiled bone
0.7845	0.4327	Absence of longitudinal fractures
0.7980	0.4249	in fresh bone
-2.0000	0.0455	Frequency of longitudinal fractures
-3.1231	0.0018	in fresh bone
0.0000	1.0000	Absence of longitudinal fractures
0.0482	0.9616	in roasted bone
0.0000	1.0000	Frequency of longitudinal fractures
0.1130	0.9100	in roasted bone
-0.8778	0.3801	Absence of fractures through diaphyseal plate
-0.8609	0.3893	in boiled bone
1.8180	0.0691	Frequency of fractures through diaphyseal plate
1.6127	0.1068	in boiled bone
1.1495	0.2503	Absence of fractures through diaphyseal plate
1.1293	0.2588	in fresh bone
-2.3812	0.0173	Frequency of fractures through diaphyseal plate
-3.8660	0.0001	in fresh bone
-0.0669	0.9467	Absence of fractures through diaphyseal plate
-0.2208	0.8252	in roasted bone
0.5585	0.5765	Frequency of fractures through diaphyseal plate
0.6080	0.5432	in roasted bone
-2.0207	0.0433	Frequency of score 0 for texture
-2.3144	0.0206	in boiled bone
-1.9687	0.0490	Frequency of score 1 for texture
-2.3601	0.0183	in boiled bone
1.1663	0.2435	Frequency of score 2 for texture
0.8911	0.3729	in boiled bone
3.0040	0.0027	Frequency of score 3 for texture
2.5074	0.0122	in boiled bone
0.0000	1.0000	Frequency of score 4 for texture
0.0000	1.0000	in boiled bone

2.1213	0.0339	Frequency of score 5 for texture
1.6856	0.0919	in boiled bone
2.0207	0.0433	Frequency of score 0 for texture
1.8310	0.0671	in fresh bone
-0.4912	0.6233	Frequency of score 1 for texture
-0.4111	0.6810	in fresh bone
-0.5745	0.5656	Frequency of score 2 for texture
-0.5232	0.6008	in fresh bone
-1.5003	0.1335	Frequency of score 3 for texture
-1.8583	0.0631	in fresh bone
0.0000	1.0000	Frequency of score 4 for texture
0.0000	1.0000	in fresh bone
-0.7071	0.4795	Frequency of score 5 for texture
-0.5858	0.5580	in fresh bone
0.0000	1.0000	Frequency of score 0 for texture
0.0697	0.9444	in roasted bone
2.4636	0.0138	Frequency of score 1 for texture
2.1083	0.0350	in roasted bone
-0.5745	0.5656	Frequency of score 2 for texture
-0.5232	0.6008	in roasted bone
-1.5003	0.1335	Frequency of score 3 for texture
-1.6223	0.1047	in roasted bone
0.0000	1.0000	Frequency of score 4 for texture
0.0000	1.0000	in roasted bone
-1.4142	0.1573	Frequency of score 5 for texture
-2.0000	0.0455	in roasted bone

Npar1way Procedure

Wilcoxon Scores (Rank Sums) for Variable BLOW

Classified by Variable TYPE

Type	N	Sum of Scores	Expected under HO	Std Dev under HO	Mean Score
f	30	945.00000	1365.0	116.171125	31.5000000
b	30	2209.50000	1365.0	116.171125	73.6500000
c	30	940.00000	1365.0	116.171125	31.3500000

Average Scores were used for Ties

Kruskal-Wallis Test (Chi-Square Approximation)

CHISQ= 52.845 DF=2 PROB> CHISQ=0.0001

Appendix B14: Number of blows for all groups

Npar1way Procedure

Wilcoxon Scores (Rank Sums) for Variable BLOWS

Classified by Variable TYPE

Type	N	Sum of Scores	Expected under HO	Std Dev under HO	Mean Score
1	15	249.00000	232.500000	24.0554317	16.6333333
2	15	215.50000	232.500000	24.0554317	14.3666667

Average Scores were used for Ties

Wilcoxon 2-Sample Test (Normal Approximation)

(with Continuity Correction of .5)

S=249.500 Z=0.685916 Prob>/Z/=0.4928

T-Test approx. significance=0.4928

Kruskal-Wallis Test (Chi-Square Approximation)

CHISQ= 0.49943 DF=1 PROB> CHISQ=0.4798

Appendix B15: Number of blows for boiled subsets

Npar1way Procedure

Wilcoxon Scores (Rank Sums) for Variable BLOW
Classified by Variable TYPE

Type	N	Sum of Scores	Expected under HO	Std Dev under HO	Mean Score
f	30	1210.50000	1365.0	114.474864	40.3500000
b	30	1360.00000	1365.0	114.474864	45.3333333
c	30	1524.50000	1365.0	114.474864	50.8166667

Average Scores were used for Ties

Kruskal-Wallis Test (Chi-Square Approximation)
CHISQ= 2.5099 DF=2 PROB> CHISQ=0.2851

Appendix B16: Number of fragments for all groups

VITA

Theresa Jo Woltanski was born in Grand Rapids, Michigan on 26 May, 1967. She spent her formative years in Kent City, Michigan, and attended elementary, secondary, and high school there. She graduated from Kent City High School in June of 1985. That fall, she entered Grand Valley State University. She earned a Bachelor of Arts degree from GVSU in the spring of 1989 with majors in both Anthropology and Spanish. She entered the graduate program at the University of Tennessee in the fall of 1989. A Master of Arts degree in Anthropology was awarded to her in the summer of 1993.

Woltanski is currently employed by the Army Central Identification Laboratory in Honolulu, Hawii.