Chapter 4 – The Strength of Bone

Section 2.2 noted that the probability that a bone will be analytically removed from an assemblage is partially related to its ability to withstand destructive forces. Although this has been touched upon in previous sections, there is a valuable body of literature that addresses the matter in considerable detail. This chapter investigates the *biomechanics* of bone and reviews the literature on how porosity, mineralisation, density and histology affect the mechanical properties of bone. First, some of the concepts and terms employed are described.

4.1: Bone Biomechanics

The strength of bone (or any other material) can be expressed in terms of *stress* and *strain*. Stress is the force that is applied to a bone and strain is a measure of the change in shape that the bone undergoes as a result of the application of that force.

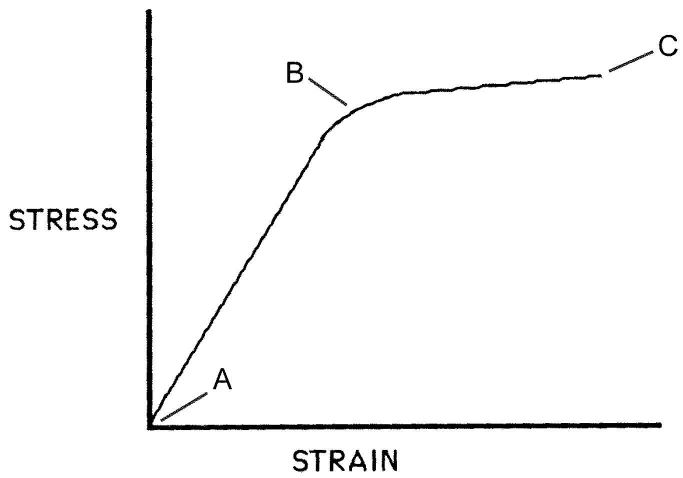

Figure 4.1: A typical stress/strain curve for the bones of a healthy adult mammal under a variety of mechanical forces. After Currey (1990a p11 Fig 1).

Figure 4.1 is a graph showing strain in a cow's femur that is under tensile stress. This is typical of stress/strain curves that would be expected for a wide range of bones from healthy adult animals under a variety of mechanical forces. Note that the two measurements are (initially) proportional to one another (Lyman 1994 p83) and that as stress increases, so does the strain ("A" to "B"). At this stage, the bone is behaving elastically, and so if the stress is removed, the bone will assume its original shape. The gradient of this part of the graph is a direct function of a property called Young's Modulus of Elasticity. Materials with a high Young's Modulus can be said to be comparatively stiff. The situation changes at "B", known as the yield point. Here, the fabric of the material has changed irreversibly and the bone will not return to its original shape when the stress is removed. The mechanical behaviour of bone after it has reached the yield point is said to be plastic ("B" to "C" on figure 4.1). The bone material fails mechanically (ie it breaks) at point "C". It is this ultimate stress that is of primary concern here, because it is fracture rather than strain that results in the analytic absence of bone from an assemblage. The area below the curve in figure 4.1 corresponds to the toughness of the bone.

Now that the relevant concepts of bone mechanics have been outlined, it is possible to explore some of the factors that influence the mechanical properties of bones.

4.1.1: Porosity

The first variable to be discussed here, porosity, has been variously described, defined and measured in the literature. McCalden *et al* (1993 p1197) defined porosity as being the percentage area of cortical bone that is occupied by pores, but excluding osteocyte canaliculi and lacunaae. Currey (1990b p837) defined these pores as being blood channels and Haversian spaces (as observed microscopically). Porosity, as defined here, differs from the measure of "pore structure" used by Hedges and Millard (1995 p157) since it takes no account of the shape or the size *distribution* of the pores. The effects of pore size and shape on a bone's mechanical properties are unclear but according to Yeni *et al* (1997 p457) are almost certainly negligible when compared with the impact of porosity – as defined by McCalden *et al* (1993 p1197) (above). The method usually adopted to measure the porosity of a bone is to observe it microscopically and to calculate the area of the sample that is occupied by pores. Porosity is a measurement usually applied to cortical bone, but since the microscopic properties of cortical and trabecular bone are essentially the same (Galante *et al* 1970 p244) there is no reason why the porosity of trabecular bone cannot be measured. In which case the spaces between the trabeculae, as well as the microscopic voids, will be counted as pores and will mean that the porosity of trabecular bone will be calculated as being considerably higher than that of cortical bone.

The contribution of porosity to the mechanical properties of a bone can be summed up in the observation that where a bone has a high porosity, there is a lower volume of bone available to absorb energy from impact, tensile or compressive forces (Currey 1979b p464) and so it is weaker. Alternatively, this decrease in strength may be due to the increased number of empty spaces in porous bone that can act as stress concentrators – rendering porous material effectively weaker (Yeni *et al* 1997 p457). Whichever of these two hypotheses is correct, it is expected that a relationship between porosity and mechanical strength will exist. Such a relationship has been identified by Evans and Vincentelli (1974 p5) where porosity of cortical bone was shown to be correlated with its ultimate compressive strength (r=0.655). Furthermore, McCalden *et al* (1993 p1201) calculated that 76% of the variation in the tensile strength of cortical bone could be explained by porosity alone. They noted the importance of the microstructure and mineral content of the sample (p1203), but stressed that porosity was by far the most important of these factors when predicting tensile strength. This result could in part be due to the fact that their experiment used samples that originated from human cadavers with a wide range of ages at death and so had a similarly wide range of porosity. This implies that when individuals of different ages are being analysed, porosity would be a useful predictor of tensile strength. The mechanical importance of porosity has also been highlighted by Yeni *et al* (1997 p457) who noted that the shear and tensile fracture toughness (the amount of energy required to propagate a crack through the sample) of cortical bone significantly decreases with increasing porosity.

Unfortunately, research into the importance of porosity for bone strength has demonstrated that although a strong relationship between the two exists, the relationship is not a simple one. The relationship identified by Yeni *et al* (1997 p457) (above) was not only non-linear (p455), but was not constant for different elements (ie femur and tibia) (pp457 - 8). The relationship between porosity and the ability for a bone to withstand impact that was identified by Currey was only true for bones of older individuals and did not hold for juvenile bones (Currey 1979b p463). In this case there seems to be an age dependent variable which, in early life, renders bone stronger than in later life. Wang *et al* (1998 p70) have failed to identify any significant relationship between porosity and tensile fracture toughness in cortical bone, and suggest that other factors might be contributing to the fracture toughness of their sample (although they do not suggest what these factors could be).

With the exception of the work by Wang *et al* (1998), previous studies seem to be in general agreement that porosity has a notable effect on the strength of a bone, by reducing strength as porosity increases. The exact nature of this effect is less universally agreed upon and is almost certainly dependant on the influence of other variables, as well as the nature (speed and direction) of the force, and whether the force is tensile, compressive, impact or shear (see section 4.2.6).

It is worthy of note that porosity is not constant across the skeleton. It varies according to the age and sex of an individual (Currey 1979b p461) as well as according to the skeletal location (Yeni *et al* 1997 p455). Consequently, if attempting to predict bone strength with reference to bone porosity, it is necessary to allow for variations in porosity caused by these variables. Nutritional status, pathological conditions and racial background are also likely to affect bone porosity, however the impacts of these variables are not entirely known and are not easily recognised and quantified in archaeological material.

It is certain that the porosity of an element is closely linked to its strength and so to its probability of becoming analytically absent from an assemblage. If the porosity of a bone (or bone part) can be predicted, then the potential for that bone (or bone part) to be underrepresented in an archaeological assemblage as the result of taphonomic processes can be assessed. In this way, taphonomic biases can be, at least partially, accounted for.

4.1.2: Mineralisation

In addition to the porosity of a bone, the level of its mineralisation has frequently been shown to have a considerable effect on its mechanical properties. The mineral content of bone refers to the amount of calcium per unit weight of bone material. It can be measured in a variety of ways. Although Currey (1979b p460) uses a chemical method to calculate mineral content, a more frequently used technique involves de-fatting the sample and reducing it to ash in a furnace (Currey and Hughes 1973 p115). By this method, the weight of mineral (remaining after ashing) can be compared to the weight of the bone including the organic component (before ashing). This provides a reasonably reliable approximation of the amount of mineral compared to collagen in a bone sample.

The impact of mineralisation on the mechanical properties of bone is best described by Currey in his various papers that explore the importance of mineralisation of bones with greatly differing functions (Currey 1969 p10, Currey 1979b pp313 - 319, Currey 1981 p18, Currey 1984 pp88 - 93, Currey 1990b pp837 - 844). In these papers Currey demonstrates that an increase of mineral content in a bone will have the effect of increasing the Young's Modulus (stiffness) and decreasing the bending strength, work to fracture and ability to undergo plastic deformation. Essentially, very highly mineralised bone is more brittle.

In his series of papers, Currey (1981 p18) also used this information to show that the level of mineralisation of a bone would reflect its physical requirements during life. Consequently, red deer antler has a relatively low level of mineralisation (59.3% compared to a figure of 66.7% as measured in the cortical bone of a bovine femur), which affords it a high resistance to impact, but means that it is not as stiff as ordinary cortical bone. This feature reflects the fact that antlers are seldom required to support weight (in the way that long bones are) but must be able to withstand the impacts involved in rutting. Furthermore, immature animal and human bone has a low level of mineralisation compared with adult bone, which renders it more able to survive the frequent impacts likely to be experienced by accident-prone juveniles. As the bone matures, its mineral content increases, affording increased rigidity and so enabling it to support the adult weight of the individual (Currey and Butler 1975 p812, Currey 1979b p469).

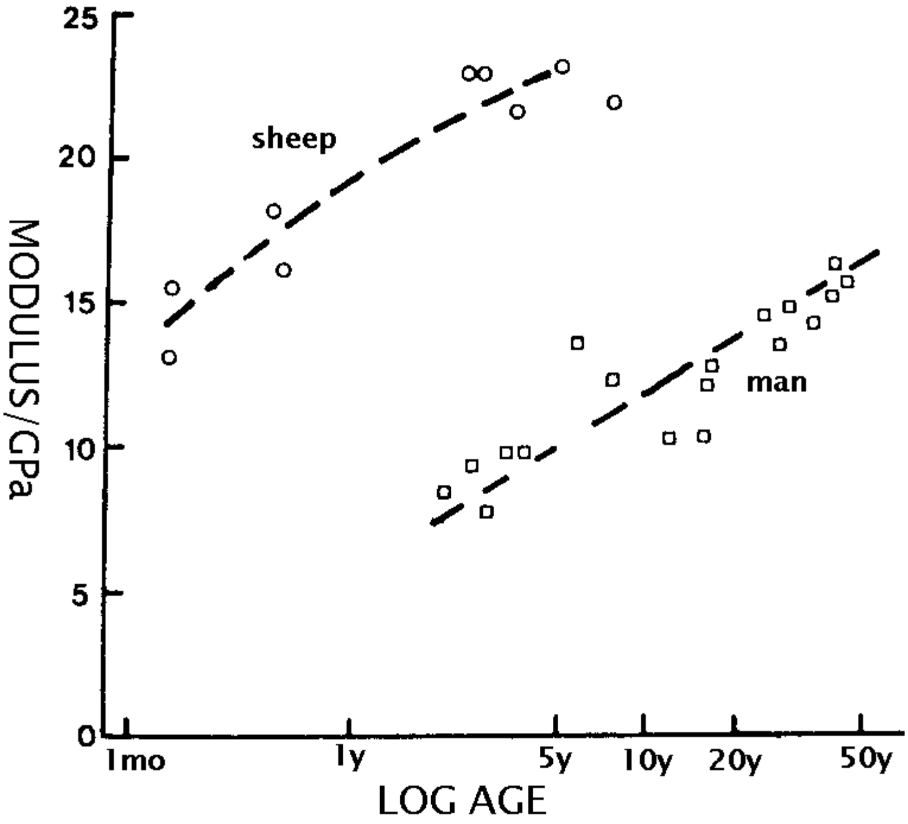

Figure 4.2: Showing how Young's Modulus (bone stiffness) increases with an animal's age. After Currey (1981 p19 Fig 4). Currey asserts that the increase in Young's Modulus is due to an increase in bone mineral content.

The correlation between mineralisation and mechanical properties cannot be doubted. The patterns described by Currey have also been identified by Berme *et al* (1977), Cheng (1998 p1440 - 1441), Turner-Walker and Parry (1995 p190) and Vose and Kubala (1959 p266). Currey (1979b p468) has suggested that mineral content can explain at least 40% of variation in impact strength and 74% of variation in tensile strength (Currey 1990b p839).

The main mechanism responsible for variations in bone mineral content is Haversian remodelling. Haversian systems are necessarily younger than the bone in which they lie and so will not have reached as high a level of mineralisation as the surrounding bone. Consequently, bone with numerous Haversian systems will have an overall lower mineral content than largely primary bone of the same age (Currey 1984 p73). The mineral content of juvenile bone is therefore lower, largely as a result of the fact that little remodelling has had an opportunity to take place. As the bone matures, Haversian remodelling will initially result in a decrease in the mineral content. Later in life, it would be expected that the mineral level would rise and then stabilise as the mineralisation of the remodelled bone is in equilibrium with the replacement of Haversian bone with new, less mineralised, Haversian systems. The frequently observed increase of mineral density in senile bone has been suggested to be a result of the slowing down of the rate of Haversian remodelling. This means that the rate of replacement of mineralised bone with new, less mineralised, Haversian systems is reduced and so there is a net increase in the proportion of older, highly mineralised osteons in the bone.

Haversian remodelling also affects aspects of the microstructure of the bone, such as its porosity, collagen orientation, and total length of cement lines. It is difficult to assess how these variables affect the mechanical properties of bone in isolation from one another. Instead, studies have assessed the impact on mechanical properties of various levels of Haversian remodelling (Currey 1969, Currey 1975 p85, Evans and Vincentelli 1974). These variables will be discussed in section 4.2.4

The mineral content of a bone clearly has a significant effect on its mechanical integrity. Highly mineralised bone is typically very stiff, but brittle, whereas bone with a low mineral content is less rigid, and stronger in impact. These properties help explain the mineral content of bones from different animals, or animals at different developmental stages. Bone mineral content has been shown to reflect the mechanical requirements of an element, ensuring that it is best suited to withstand the particular mechanical stresses under which it is likely to be placed.

4.2.3: Density

Strictly speaking, bone density refers to the ratio of mass to volume of a bone (see section 3.2). Consequently, it is largely related to bone porosity (although the chemical content of a bone also plays a minor role). Bone density and porosity might be seen as being two measurements of essentially the same variable. However, in the example discussed below, the authors explicitly claimed to be measuring bone density. Furthermore, the methods used to measure bone density in the following examples were markedly different from those used by the authors referred to in the discussion of porosity (above). It is for these reasons that this section has been kept separate from any discussion of porosity.

Any discussion of bone density is hampered by the fact that different authors have used the term “density” to define a variety of bone properties. Chapter 6 describes some of the many methods that could be used to measure bone density. Lyman (1984 p266 - 267) has highlighted the fact that most of the methods used to measure bone density in fact produced values that only approximate true density. The data produced by Lyman himself (and other researchers – Elkin 1995, Kreutzer 1992, Willey *et al* 1997) (see chapter 6) were more probably a hybrid of mineral content and porosity. The values used by Vose and Kubala (1959 pp263 - 265) were obtained by assessing the radiodensity of their bone samples. The importance of density, as measured by radiography, is clear from the high correlation obtained by Vose and Kubala (1959 p266) between the radiodensity of their samples and the ultimate bending stress of the bones from which they were taken (r=0.94). A similar result was obtained by Martin and Ishida (1989 p425) who found density to be an important predictor of the tensile strength of cortical bone. Cheng *et al* (1998 pp1440 - 1441) found a similar relationship between bone mineral density (as measured by DEXA – see section 6.3.5) and impact strength.

The method used by Carter and Hayes (1976 and 1977) did not seem to take into account the mineral content of their samples. Instead a value of "apparent density" was calculated by "dividing the hydrated tissue weight by the bulk volume of the specimen as determined by micrometer measurements" (Carter and Hayes 1977 pp955 - 956). This figure approximates Lyman's "bulk density" (1984 p264) and is more reliant on porosity than mineral content, but has been used by Carter and Hayes (1976 and 1977) to predict the compressive behaviour of marrow filled and "clean" trabecular bone. In their study, Carter and Hayes demonstrated that compressive strength is approximately proportional to the square of the bone's apparent density. These observations did not hold for bones with marrow *in situ* when the strain rate was high. In these cases the compressive strength of the samples was considerably increased (Carter and Hayes 1977 p960).

Since the bone density values discussed above are effectively measures of either porosity or a combination of porosity and mineral content (depending on the measurement method being used), they are likely to vary according to the same factors that control porosity and mineralisation. Consequently, density would be expected to change according to the skeletal location and the age, sex, breed or race and health of the individual (Vose and Kubala 1959 p268). Furthermore, diagenetic factors must be considered (see section 3.4), since these are known to affect the porosity and mineral content of buried bone. Turner-Walker and Parry (1995) carried out mechanical experiments on archaeological bone and concluded that it is possible that even in only slightly destructive burial environments, buried bone will experience a rapid loss of apparent density (or more probably an increase in porosity). This would have a deleterious effect on its mechanical properties (Turner-Walker and Parry 1995 p190).

Despite the lack of consensus on the definition of density and how it should be measured, all of the authors discussed above have noted that their own value of bone density can be used to predict bone strength with reasonably high reliability. Of particular interest here are the results of the studies that correlated radiographically based values of density to various mechanical properties of bones (Vose and Kubala 1959 p266, Martin and Ishida 1989 p425, Cheng *et al* 1998 pp1440 - 1441). These results suggest that radiographically derived values for bone density can be used successfully to predict the analytical absence of bones from archaeological assemblages. These values can therefore be used to attempt to account for taphonomic biases in the archaeological record. This fact will form the analytical basis of this project.

4.2.4: Bone histology

It is generally agreed that porosity (or density) and mineralisation contribute the most to the mechanical integrity of a bone (especially when a wide range of bone types is being examined (Martin and Ishida 1989 p425, McCalden *et al* 1993 p1203)). These variables have been described above and so any variation in bone mechanical properties due to histological variation that can be attributed to mineral content or porosity (Currey 1975 p84, Martin and Ishida 1989 p424) need not be discussed further. However, other histological variables are certainly worthy of some attention.

Yeni *et al* (1997) measured a number of histological variables independently of mineral content or porosity (including the average size and the total area occupied by Haversian systems in the sample). They concluded that the number of osteons per unit area was significantly – positively – correlated with shear fracture toughness in the tibia and femur of human cortical bone. The fact that the frequency of osteons and tensile fracture toughness were not correlated in the femur suggests that in this case some other independent variable was responsible for this mechanical property (Yeni *et al* 1997 p457). These observations are in general agreement with the findings of Corondan and Haworth (1986 p214) and Evans and Vincentelli (1974 p9) who noted that cortical bone is more prone to catastrophic failure in parts of the bone where osteons are comparatively scarce. Yeni *et al* (1997 p456) also showed that the mechanical integrity of a bone decreased as the average size of its osteons increased. This can be explained by the fact that where osteons are larger, there will necessarily be fewer of them per unit area.

Contrary to these findings, Evans and Bang (1967 p85) have noted that as an animal matures and the number of Haversian systems increases, the tensile strength of its bones is *reduced.* This, they suggest is a consequence of there being an increased number of cement lines or pores (in the form of Haversian canals) that can act as crack initiators. This suggestion remains contentious, since it is possible that Haversian canals and cement sheaths around Haversian systems can also act as crack stoppers – thereby strengthening the bone (Currey 1984 p86).

Although the nature of Haversian systems undoubtedly has *some* effect on the mechanical properties of a bone, Burr (1980 p121) notes that:

> High correlations between mineral density and microstructural remodelling preclude the possibility of separating the effects of density from those of microstructure when determining the mechanical properties of bone. This suggests that density measurements may be as effective as microstructural characteristics in explaining variation in the mechanical properties.

It seems that variations in mechanical properties that can be attributed to the size or number of osteons, are more likely to in fact be the product of variations in mineral content or porosity.

4.2.5: Collagen orientation

Another histological variable that has been shown to affect a bone's mechanical behaviour is that of collagen orientation. The collagen fibrils in bone are known to be orientated in different directions in various lamellae. The orientation of these fibrils can be observed in transverse thin sections of bone, viewed under polarised light. In these, longitudinally orientated fibrils (those running approximately parallel to the long axis of the osteon) appear dark, while circumferential (spiralling) fibrils appear light.

According to Johnson (1985 p167), bones whose collagen is longitudinally orientated will have a greater tensile but lower compressive strength than bone with collagen that is circumferentially orientated. This is in concordance with the conclusions of Ascenzi and Bonucci (1967 p385), Evans and Vincentelli (1974 p6) and Martin and Ishida (1989 p425). There is little information available as to the relative importance of collagen orientation, as compared with other factors discussed in this section. Evans and Vincentelli (1974 p5) as well as Currey (1975 p86) claim that the mechanical effects of bone mineral content are comparatively more important than the mechanical impact of collagen orientation. Even Martin and Ishida (1989 p425), who stress the mechanical importance of collagen orientation in bovine bone, concede that mineral density is a much better predictor of bone strength when a wide variety of bone types are being studied.

Collagen orientation is a response to physical stresses on the bone. Longitudinally oriented collagen fibrils have been observed to occur in the lateral-anterior part of the femoral cortex of humans (Martin and Ishida 1989 p425). This is the part of the bone that is in tension during walking or running and so collagen orientation might be a response to this stress. Furthermore, younger, un-remodelled bone has a more longitudinal collagen orientation (Martin and Ishida 1989 p425). Although no adaptive explanation has been offered here, it is apparent that age has an effect on collagen orientation (and therefore mechanical behaviour).

The orientation of collagen fibrils is one of the many features of bone that has been suggested to influence its mechanical behaviour. Although this is undoubtedly true, its seems likely that other factors have a more profound importance, especially when a wide ranges of bones are being compared.

4.2.6: Direction and nature of the load

The last two factors that can impact upon the mechanical behaviour of bone that will be discussed here do not relate to the characteristics of the bones themselves, but rather concern the nature of the force applied to the material. They are the direction and nature of the loading.

The direction of loading relates to the direction of the load applied to the bone in relation to its physical characteristics. Lyman (1984 p86) describes how the orientation of collagen fibres in cortical bone produces a “grain”. This takes the form of lines of weakness, usually along the long axis of the bone. Consequently, bone will be stronger if the loads applied are in the direction of the grain rather than if they are at right angles to it. Similarly, trabecular bone has a sort of grain, produced by the orientation of the individual trabeculae. Galante *et al* (1970 pp244 - 245) demonstrated that trabecular bone from human vertebrae has differing mechanical responses, depending on the direction of the load relative to the bone sample. They demonstrated that samples loaded in the superior-inferior direction were more than twice as strong as those loaded medial-laterally (Galante *et al* 1970 p241). The importance of orientation has also been noted (although not quantified) by Currey (1990b p842) and Wang *et al* (1998 p71). Generally speaking, bone tends to be strongest in the direction in which it is loaded during normal life.

The nature of the load, as described here, involves the speed of the application of force and whether it is a tensile, compressive or shearing force. The mechanical impact of the speed of the application of force acting on a bone has been addressed in some detail by Currey (1975). In his paper, Currey (1975 p85) demonstrated that a 1000-fold increase in strain rate produced a 50% increase in the tensile strength of bovine cortical bone. Varying the strain rate also affected other mechanical properties of the samples (yield strength, strain at yield and modulus of elasticity (Currey 1975 p85)), but since these properties do not lead directly to bone fracture (and eventually – archaeologically speaking – analytic absence), they are of limited importance to this project. Carter and Hayes (1976 and 1977) paid further attention to strain rate when they investigated the effects of varying strain rate on the compressive behaviour of trabecular bone. In their papers on the subject, they determined that (although bone density remained the single most valuable predictor of bone strength (Carter and Hayes 1977 p956)) the compressive strength of trabecular and cortical bone was proportional to the strain rate raised to the 0.06^{th} power (Carter and Hayes 1977 p958). They noted however, that where the strain rate was high and the bone sample still contained marrow, this rule was not robust (Carter and Hayes 1977 p956). In these situations the compressive strength of the bone samples was greatly increased. This suggests living or fresh bone is more resistant to high impact. Consequently, the same bone is likely to react differently to butchery (high impact with marrow), gnawing (low impact with marrow) or trampling when weathered (low impact without marrow).

Any force that can be applied to a bone can be considered as being either compressive, tensile or shear. Other forces, such as impact, bending or twisting consist of different combinations of these, often acting in different relative directions to one another (Johnson 1985 p170). A good example of how the properties of a bone affects its ability to resist shear, tensile and compressive forces in isolation from one another (rather than simply making it “stronger” or “weaker”) can be found in the case of collagen orientation, discussed above. The steep spiralling of collagen fibrils around the longitudinal axis of the osteons within a bone has the effect of increasing the tensile strength of that bone. However, it also has the effect of decreasing the bone’s compressive strength (Johnson 1985 p167). Similarly, an increased number of osteons per unit area in the cross-section of femoral cortical bone will result in an increase in both its shear and tensile fracture toughness, although the effect on tensile fracture toughness is more marked than the effect on shear fracture toughness (Yeni *et al* 1997 p457). In these examples, altering the physical properties of bone does not have the effect of altering all of the mechanical properties uniformly. Because of this non-uniformity of the reaction of bone mechanical properties to varying its physical properties, researchers have tended to standardise the type of force used in any individual experimental circumstance. An unfortunate consequence of this is that little is known about how the different types of force relate to each other given a specific set of physical criteria. However, this project will be concerned largely with mineral density as its main variable, and the review of the literature suggests that increasing density (or more precisely, mineral density) increases tensile, compressive and shear strengths (albeit to differing degrees).

It seems that the mechanical properties of a bone are not only controlled by its physical properties, but are also partly dependent on the nature and direction of the force being applied to it. Some forces likely to be experienced by archaeological bone as it undergoes taphonomic alteration could probably be modelled. For example, while being butchered, a bone is likely to undergo impact of an approximately predictable force and direction, in predictable locations, while the bone is in a specific orientation. Given this information, it is theoretically possible to model any given butchery process in terms of mechanical factors, so that fragmentation patterns can be predicted. However, such a model would not be able to account for deviations from the standard processing pattern by the butcher. Also, the data required to produce such a model and the mechanical knowledge needed to implement it is not yet available. The same is the case for mechanically modelling other taphonomic processes such as gnawing and trampling. Until models of this sort are rendered viable by significant increases in our understanding of mechanical and archaeological factors, it is necessary to view the mechanical behaviour of bone on a more general level. It has been the habit of archaeologists to assume that the effects of destructive forces that act on bone are constant, regardless of their direction, rate or the extent to which they are tensile, compressive or shear. Although it is to some (unknown) degree incorrect, archaeological interpretations that implicitly make this assumption have proved reliable and so it can be incorporated into this project.

In addition to the properties of the material itself, the direction and nature of the load being applied can have a significant impact on the durability of a bone. Bone is comparatively weak in some directions, but much stronger in others. This reflects the forces that a bone would normally experience during life. Similarly, the speed at which a load is applied will to some extent govern the bone's reaction to it. Both of these factors have direct archaeological implications since a particular destructive process may have associated with it a specific direction and speed.

4.3: Summary

The complexity of bone as a material is reflected in the complexity of its mechanical behaviour. With regards to mechanical properties, "there is, of course an infinity of variables that are potentially of importance, of which the great majority are un-measurable" (Currey 1990b p842), and only a few of the more important ones have been discussed here. The variables that are known to contribute to mechanical integrity are often interdependent (eg the number of osteons per unit area, porosity and mineralisation (Yeni *et al* 1997 p457)) or operate in a non-linear fashion (eg apparent density (Carter and Hayes 1977 pp858 - 961)). The relative contributions of different variables to the overall mechanical integrity of a specimen are little understood. However, "it seems then that an understanding of the related effects of porosity and mineralisation still provides the most adequate picture of the mechanical behaviour of bone" (Burr 1980 p120). It is largely for this reason that this project will concentrate on the measurement of bone mineral density.

Furthermore, it is clear that the mineral density of bone varies with the age of an animal. Currey (1979b p461) reports a three-fold reduction in the impact strength of human cortical bone between birth and about 95 years of age, which he attributes almost entirely to variations in mineral density. This suggests that an understanding of how the mineral density of different bones changes with age will be an invaluable tool when predicting which bones are likely to be removed preferentially from an archaeological site through fragmentation.

The above description of the mechanical behaviour of bone is taken almost entirely from the medical literature. These reports are generally concerned with the fracture properties of fresh (usually cortical and often human) bone. The only investigation to assess the mechanical properties of archaeological bone is that of Turner-Walker and Parry (1995). Other works (Lyman 1994 pp82 - 87, Johnson 1985) have noted and made use of mechanical information, but have not contributed to that information directly. Investigations such as these are few and far between. Consequently, there is something of a paucity of knowledge about how bone that is not fresh will react to mechanical forces. Weathering, cooking and diagenetic processes all bring about alterations in a bone's mineral content, porosity and the integrity of its collagen network and so bone that has undergone any of these processes cannot be assumed to have the same mechanical properties as fresh bone.

The information from the medical literature, which has been drawn on above, highlights certain bone properties as being important in providing a bone with its mechanical integrity. What is required is an assessment of how these properties vary between individuals. This, in turn, will enable the impact of these variables on the mechanical properties of the bone to be assessed. Any conclusions reached will be founded on the results of reliable laboratory experiments, rather than comparatively uncontrolled field experiments or observations.

This chapter has demonstrated that the ability of a bone to withstand destructive forces is intimately linked to its density. However, a number of other factors (eg collagen orientation and the direction and nature of the force) are also potentially important. One of the research objectives of this project is to assess the extent to which bone density data alone are capable of predicting the behaviour of bone under mechanical pressure.