Chapter 6 – The Measurement of Bone Density

This chapter will address aspects of the measurement of bone density. Firstly, the methodologies used by previous archaeological investigations will be reviewed and assessed. Each relevant investigation will be discussed in turn (in chronological order). Next, the actual methods for measuring bone density will be described and the various advantages and disadvantages of each will be highlighted. These reviews will serve as a background and foundation for the methodology developed for this project (both the measurement method and experimental material used).

6.1: Introduction

It is desirable that this project builds upon previous works, rather than merely existing alongside them. Consequently, it is necessary to refer to earlier methods, noting their strengths and weaknesses and, where beneficial, incorporating such observations into the design of the methodology used by this project.

The literature contains numerous reports of a broad range of means of determining bone density, which tend to fall into two categories. The first, and largest, category addresses numerous clinical questions regarding bone development and pathology (eg Brickley 1997, Farquharson *et al* 1997, Wang *et al* 1998, Yeni *et al* 1997, Yeni *et al* 1998,). Since these papers usually use fleshed or even live samples, and focus on the importance of bone density to an individual during life, the methods involved are of limited relevance here. More relevant to this study are the papers from the second category: those that attempt to assess the durability of bones in the archaeological record by measuring the density of modern reference material. In order that the advantages of these methods can be maximised and any mistakes avoided, each of these previous studies must be examined in turn. The list of studies discussed below is not intended to be exhaustive, but covers the vast majority of relevant studies. In doing so, it discusses all of the issues that must be considered when designing a method that is appropriate to this project.

6.2: The Methodologies of Previous Archaeological Investigations

6.2.1: Brain 1969

Although he was not the first to note the influence of density (often referred to as robustness or strength in the earliest papers (eg Steenstrup 1862)) on the formation of

archaeological assemblages, Brain (1969) was the first to attempt to quantify this variable. Brain examined only the long bones (humerus, radius, femur and tibia) of a single modern goat. Goat was chosen as the taxon to be studied, since the data obtained was to be applied to an assemblage of goat bones. He cut the bones in half, transversely, and weighed each half separately. The volumes of each portion were ascertained by sealing up all of the foramen or other holes in the bone portions with Plasticine, immersing them in water and measuring the volume of displaced liquid. By using the equation:

$$\text{Specific Gravity} = \frac{\text{Weight of dry bone}}{\text{Total volume of bone + Plasticine + air spaces}}$$

Brain produced a value for the specific gravity of the proximal and distal halves of each long bone concerned. Subsequently, Lyman (1984 p266) has pointed out that this is not a measurement of specific gravity, but rather is a hybrid of true and bulk density. Despite this semantic error, Brain still showed a good correlation between the "specific gravity" of each bone portion and both their survival of destructive taphonomic processes and their fusion times. Furthermore, despite any shortcomings of his method, he still ably demonstrated that density was an important factor in determining bone survival and that the matter certainly warranted further investigation. In this respect, Brain's paper was seminal. However, the pedant might note a number of shortcomings in the paper. Perhaps most obviously, the sample size is extremely small (only four bones from a single individual). Such a small sample could easily mask any bias caused by the sex, nutritional status, breed, season of death, or even the age of the individual under analysis. So that the effects of these variables might be minimised, a much larger sample must be employed. Similarly, looking at such a narrow range of elements from only one taxon has two disadvantages. First, that valuable data on the variation of bone density across the skeleton and between taxa may be missed. Second, the data produced are of limited use in interpreting archaeological assemblages, which usually contain more than one taxon and a wide range of skeletal elements.

Brain was correct to identify the importance of measuring the distal and proximal ends of the bones separately, since they do, in fact, often have different densities. Unfortunately, by measuring the proximal epiphysis and proximal shaft together (and the same for the distal end) he ran the risk of masking variation between the bone ends. This is because it is now widely recognised that the trabecular bone of the epiphysis and the cortical bone of the shaft are effectively different materials and so

should not be measured together. Brain was effectively measuring the *average* density of the trabecular and cortical bone from the material in question. Many subsequent researchers have avoided reproducing this error: a course of action that will also be adopted here.

Also worthy of note here is that, by cutting the bones in half, Brain's method was destructive. Using a method that destroys bones is not ideal. Well-provenanced reference material is valuable and its destruction is ill-advised, except in the most extreme of cases.

Now, to turn briefly to the method by which Brain calculated bone density. By measuring the volume of each sample by immersing it in water, Brain risked over-estimating the final density value. This is because bones are porous to some extent, and during immersion would have been liable to absorb a small volume of water (despite Brain's precaution of plugging any macroscopic holes with Plasticine), thus providing an artificially low volume. The rate at which a bone absorbs water in this way is likely to vary according to its weathering stage (Behrensmeyer 1975) as well as the age of the animal and natural variations within the skeleton. Following Brain's original work, no attempt has been made to model this variable and so it cannot be controlled experimentally.

6.2.2: Behrensmeyer 1975

Behrensmeyer (1975) was less interested in the physical destruction of bones as their transport away from the site by fluvial processes. The sample that she chose to study consisted of recent specimens of hippopotamus, zebra, a large and a small antelope (*Redunca* and *Damaliscus*) a pig (*Hylochoerus*) a sheep and parts of two crocodiles and various fish species. Like Brain, she measured the density of her sample by combining the weight of each sample with its volume (as determined by submersion in water). However, this time the weight was that of each sample after it had been immersed in water for five minutes or "until the bubbling had stopped" (Behrensmeyer 1975 p485). Similarly, the volume was ascertained by measuring the volume of water that was displaced when this saturated bone was immersed. The formula being used was therefore:

$$\text{Density} = \frac{\text{Weight of the saturated sample}}{\text{Total volume of bone + air spaces}}$$

As was the case for Brain, the resulting value is also one of a hybrid of true and bulk density. However, the two sets of results are not comparable, since the proportion of air spaces included in the equation is different in each and the volume of Plasticine does not contribute to Behrensmeyer's values.

This method contains many of the same problems and advantages as that of Brain (1969 – see above). For example, both studies measured cortical and trabecular bone together, the sample size was small and the rate at which the samples absorbed water was still likely to affect the results adversely (although perhaps to a lesser extent). It is worthy of note that despite this, repeated measurements of the same sample produced an error of less than 5%. Also, Behrensmeyer obtained a good correlation between her values of density and the susceptibility of each relevant bone part to fluvial transport.

6.2.3: Boaz and Behrensmeyer 1976

Another, later, investigation into the factors affecting fluvial transport of human bone was the one carried out by Boaz and Behrensmeyer in 1976. In this case, human bones were examined. It is important that the subjects of this study were whole bones and naturally fractured portions of bones, rather than predefined parts of each bone. The elements themselves were those which were made available to the researchers and were not specifically chosen according to their ability to answer specific research questions. Boaz and Behrensmeyer defined "density" (later redefined as bulk density (Lyman 1984 p267)) using the equation:

$$\text{Density} = \frac{\text{Wet weight of the bone in air}}{\text{Wet weight of the bone in air - weight of the bone in water}}$$

The "wet weight of the bone in air" was determined by weighing each element after it had been submerged in water for at least 5 days. The weight of the bone in water was determined simply by suspending the saturated bone in water while taking a weight reading.

The convincing results obtained by the authors (who also had some success in using element shape and orientation as predictors of an individual bone's susceptibility to fluvial transport) is encouraging even though their study is not immediately comparable to this one. They have provided compelling evidence that bulk density is an important factor in mediating fluvial transport. In addition, Boaz and Behrensmeyer's selection of complete or already (arbitrarily) broken bones, although non-destructive,

would not be suitable for this particular piece of research. This type of analytical sample was quite suitable for the experiment in question, but is less so for a study such as this which is looking at the archaeological durability of isolated portions of bones.

6.2.4: Binford and Bertram 1977

A further variation on this method was developed by Binford and Bertram (1977). They conducted the first investigation to attempt to address the impact of age at death of an individual on its bone density. The animals examined were three sheep (aged 6, 19 and 90 months) and one caribou (aged 30 months). No justification for this choice of sample material was given in the text, but it seems likely that it was intended to reflect the taxa most usually recovered from the ethnographic assemblages under investigation (those of the Navajo Indians and Nunamiut Eskimos). Binford and Bertram also recognized the need to ensure that their samples had a controlled moisture content before weighing, in order to obtain standardized weights for each sample. The details of how this was achieved are described in their paper (Binford and Bertram 1977 pp107-109). Like those who went before them, Binford and Bertram ascertained the volume of each sample by immersing it in water and measuring the volume of displaced liquid. They overcame the problem of the porous bone absorbing an unknown volume of liquid and so returning artificially low results by coating each sample in a thin, impermeable layer of paraffin wax prior to immersion. Consequently the equation used to obtain bone density was:

$$\text{Density} = \frac{\text{Weight of the bone in air}}{\text{Total volume of the bone + air spaces + wax coating}}$$

Lyman (1984 p267) has since redefined this measurement as being "an imprecise approximation of bulk density because the volume of wax did not enter into the calculations". Clearly, this method is quite similar to that of Brain (Brain 1969), having most of the same advantages and drawbacks. It is likely that the improvements on Brain's method that were made by Binford and Bertram (ie the controlling of moisture during weighing, and the use of a wax coating rather than Plasticine plugs) resulted in a more accurate result. However, the authors themselves admit that the procedure was "not ideal" (Binford and Bertram 1977 p107). Of some importance here is the fact that the use of a wax coating, while undoubtedly improving the quality of the results, cannot be used here, since it is effectively destructive (being practically impossible to remove completely).

Binford and Bertram's report refers to the weighing and measuring of "anatomical parts" (p107). Since results were obtained for proximal and distal parts separately, it seems reasonable to assume that these "anatomical parts" are those parts for which density information was eventually produced (eg the distal and proximal ends of long bones rather than complete bones). Unfortunately, it is impossible to say whether these anatomical parts consisted of ends only or (less ideally) of ends and shafts combined.

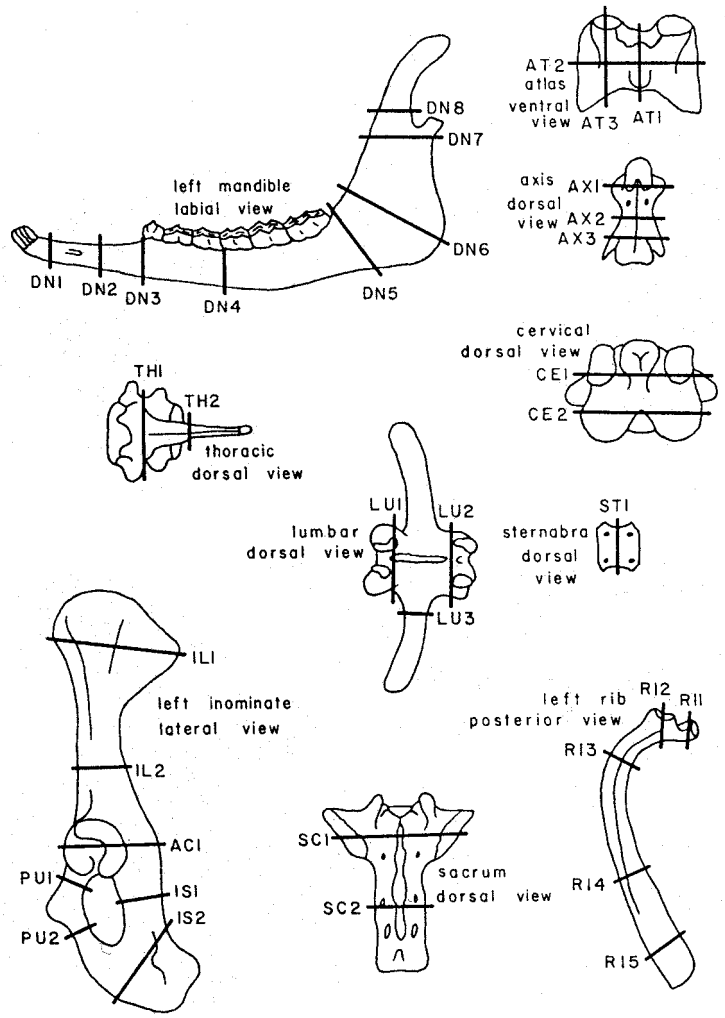
6.2.5: Lyman 1984

After the research of the 1970s there seems to have been something of a hiatus in this field of research. It was some seven years before another methodology was published (Lyman 1984). In his research Lyman deviated from the types of method outlined above and adopted photon absorptiometry as his measurement technique (See section 6.3.4 - 6.3.5). Lyman went to some lengths to explain and justify practically all of his methodology. His sample, for example, (13 deer (*Odocoileus* sp.) 3 partial domestic sheep (*Ovis aries*) and one partial pronghorn antelope (*Antilocapra americana*)) was intentionally chosen to reflect the most abundant taxa normally found on North American archaeological sites. All individuals examined were modern and adult or sub-adult. His sample size, although still rather small – especially for the sheep and antelope – was originally intended to be larger, but difficulties in obtaining material prohibited this.

Lyman was also the first to specifically select multiple measurement points (or *scan-sites*) across each bone, rather than relying on the measurement of "proximal end" and "distal end" that had been used previously. This enabled a more detailed and accurate picture of the way in which density varied across his material. It also provided data that were compatible with many of the more modern site recording systems (such as that used at Çatalhöyük), which tend to record bone presence according to the specific part of a bone represented, rather than by which end any given fragment is from. Lyman specified four criteria by which scan-sites were chosen. These were:

1) Known structural density variation within each bone.
2) Ease of location and definition to assure similarity of measurement of a particular scan-site across multiple samples.
3) Suspected or known differences in density based on previous studies.
4) Marked discrepancies in the frequencies of skeletal fragments in archaeological and paleontological sites.

The scan-sites finally chosen are shown in Figure 6.1.



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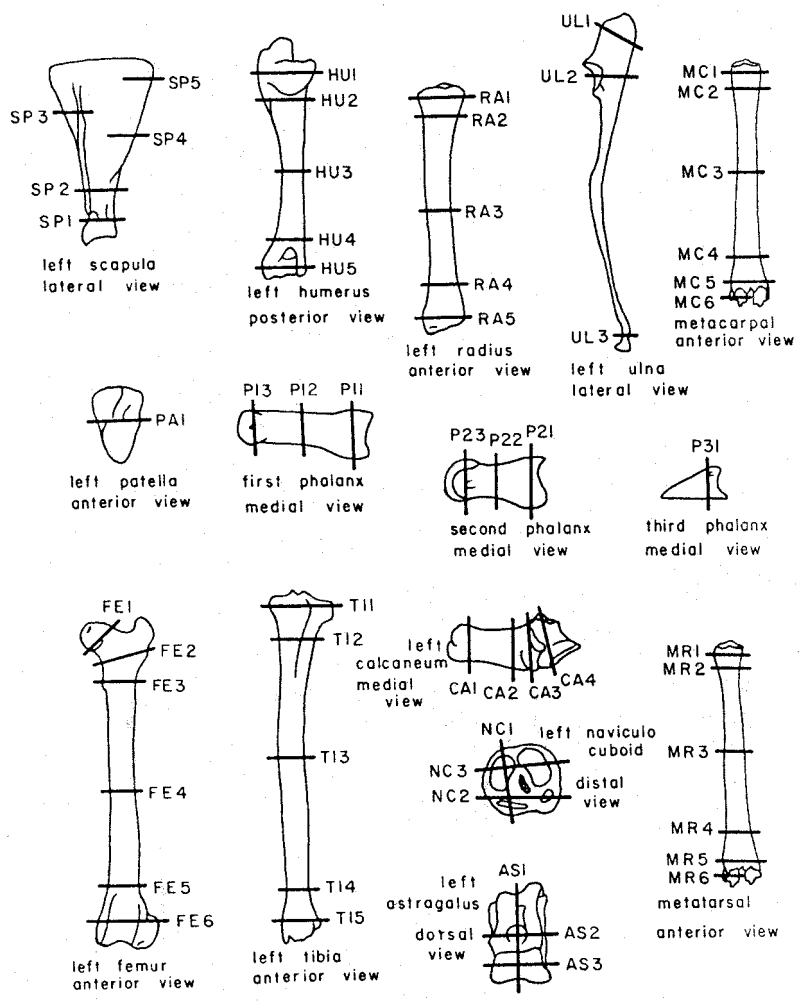

Figure 6.1: The scan-sites chosen by Lyman. From Lyman (1984 pp274 - 275 Fig 2).

A further, and important, point to note here is that the photodensitometer used in this study produced a value for the mineral density per unit squared of the sample – termed "linear density" (or "LD") by Lyman (p273). In other words, the device did not account for the thickness of any of the samples (this is because it was originally designed for longitudinal studies of live specimens, where the thickness of the bone would remain the same for each reading). The most important consequence of this is that a dense but thin bone could appear to have the same density value as a thicker, less dense bone (Kreutzer 1992), (See figure 6.2).

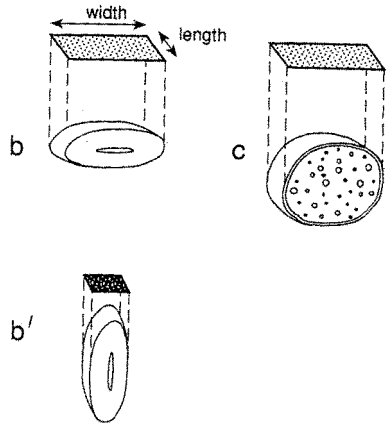

Figure 6.2: Diagramatic representation of the contribution of bone thickness to radiodensity. Note that b and b′ are the same bone, but the two different orientations result in different linear densities being returned. b has a greater structural density than c, but because it is thinner, the same linear density is returned. From Kreutzer (1992 p282 Fig 3).

Lyman attempted to overcome this problem by dividing the "linear density" returned by the machine by the maximum thickness of the bone along the line of the scan-site. This simple calculation provided a value for what Lyman called "volume density" (or "VD"):

$$\text{Volume density} = \frac{\text{Linear density}}{\text{Maximum thickness of bone at scan-site}}$$

This calculation involved the assumption that all of the samples had regular rectangular cross-sections. Since this is clearly not the case, Lyman's volume density is likely to be artificially low. It would have been possible to overcome this problem by slicing the samples in half and mechanically measuring the true cross-section of the samples. However, one of the main advantages of this method was that it was non-destructive (unlike most of the work reviewed so far) and to cut the bones would have been far from desirable.

A further potential for error in this method was that the densitometer was actually measuring the *mineral* density of the samples. Mineral density could be described as a combination of bulk density and the degree of mineralisation of the bone. Both of these variables are known to have an effect on bone strength (Carter and Hayes 1976, Cheng *et al* 1998, Currey 1969 & 1981, Martin and Ishida 1989, Turner-Walker and Parry 1995) but their relative contributions to strength are unknown. Consequently, an increase in the mineral density of a bone (as measured by densitometry) could be due to either a higher level of mineralisation or to a higher bulk density. The exact effects of this mineral density increase cannot, therefore, be predicted. Essentially, Lyman is

obliged to assume that the only factor affecting his mineral density values is variation in bulk density. Despite this, Lyman demonstrated in his paper that his mineral density values were indeed comparable to the values obtained by Behrensmeyer (1975), Binford and Bertram (1977), and Brain (1969). He also convincingly used his mineral density values to explain the bone frequencies from a number of archaeological and ethnographic sites. The appropriateness of Lyman's original work (and his later work on marmot (*Marmota* sp.) bones, (Lyman *et al* 1992) is evident in that many subsequent researchers have used this original work as a template on which to base their own research, each adding their own modifications and improvements. These, and other, subsequent works will now be examined in turn.

6.2.6: Lyman, Houghton and Chambers 1992

Lyman was also engaged in a study that compared the bone density of three yellow-bellied marmots (*Marmota monax*) and one woodchuck (*M. flaviventris*) with those of deer and bison (Lyman *et al* 1992). All of the methods used to obtain the density values of the marmot skeletons were essentially the same as those used by Lyman (1984 – described above). Consequently, the relative merits of this study do not differ from those described above, for Lyman (1984) and need not be discussed further.

6.2.7: Kreutzer 1992

Kreutzer (1992) expanded the list of taxa for which bone density values were available by measuring the skeletons of 12 modern bison. She then compared her data with those from Lyman (1984) in order to test her hypothesis that the differences in anatomy and behaviour (eg the gait of the animals) would produce corresponding differences in their bone density and hence the survival profiles of the archaeological remains. Kreutzer followed essentially the same methodology as Lyman, with the addition of a number of elements, such as the hyoids and carpals, and the exclusion of a number of scan-sites, which the anatomy of the bison rendered impossible to measure. A more important divergence from Lyman's methodology was that Kreutzer attempted to improve upon Lyman's method of converting linear density into volume density. Rather than dividing linear density by the maximum thickness of the bone, she measured the bone in several places in order to produce a crude profile of the sample (see figure 6.3).

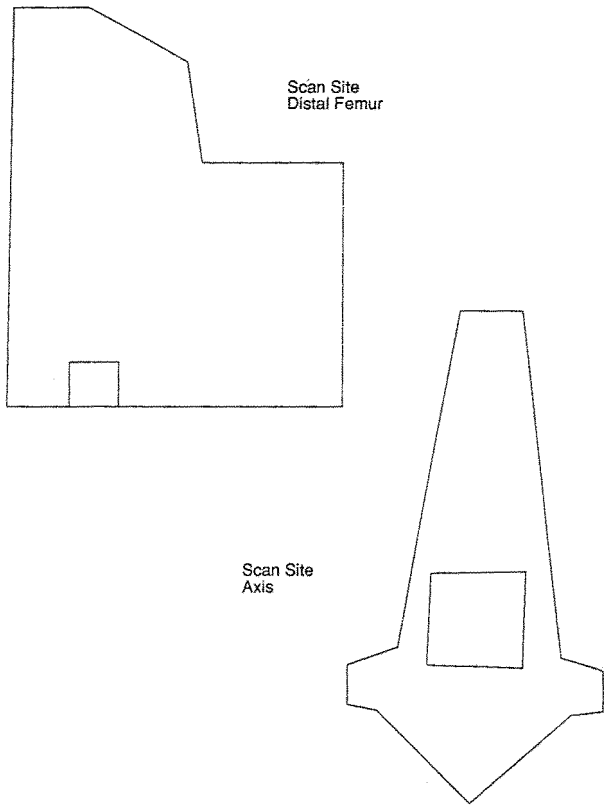

Figure 6.3: Showing two of the crude cross-sections used by Kreutzer (1992), generated by taking multiple measurements of each bone. This contrasts with Lyman's (1984) use of the assumption that his material had rectangular cross-sections. From Kreutzer (1992, p284 Fig 4).

This, she argued, would provide a more accurate representation of the cross-section of the bone and would overcome the problem of Lyman's (incorrect) assumption that the cross-sections of his various samples were all rectangular.

$$\text{Volume density} = \frac{\text{linear density}}{\text{Approximate average thickness of sample}}$$

Note that the thickness used in this equation is an average one calculated by taking multiple measurements of the bone in question. It is not the true value.

Kreutzer had clearly improved upon the work of Lyman, while maximizing the advantages of his method. Her contribution can be seen in that the more accurate representation of sample cross-section caused a higher value for the

"Atlas 2" scan-site (AT2 – see figure 6.1) to be returned for bison than for deer. Further differences between the two taxa were ascribed to differences in anatomy and behaviour as was originally hypothesized.

One negative aspect of Lyman's and Kreutzer's work (and that of many subsequent authors) is that photon absorptometers are very expensive. They are primarily medical instruments and so are not readily available to archaeologists who are engaged in non-medical research.

6.2.8: Butler and Chatters 1994

In 1994, Butler and Chatters added salmon to the list of taxa for which density values were available. The material measured was from 10 modern male and female chinook salmon (*Oncorhynchus tshawytscha*). The elements to be measured were chosen in order to obtain values for bones with a variety of positions in the skeleton, shape, and abundance in the archaeological record. The measurements were taken using dual energy X-ray absorptiometry (DEXA). Despite the use of this slightly more advanced technique, it was still necessary to account for the cross-sectional area of the bones. This was, the authors reasoned, even more important in this study, due to the highly irregular shapes of salmon bones. Butler and Chambers measured the volume of each element to be measured using the *hydrostatic weighing method.* This involved immersing each element in water. Rather than reading the volume of water displaced off a graduated scale, the volume of displaced water was calculated by weighing it. The equation being used was therefore:

$$\text{Volume density} = \frac{\text{Linear density}}{\text{Weight of displaced water}}$$

Repeated measurements on the same elements produced a maximum difference of only 2.9% between equivalent measurements. Also, the bone mineral densities produced by this method were shown to differ by 6% from the "true" bone mineral densities, as calculated by loss on ignition of the bones. This slightly higher error of 6% could be due to the fact that DEXA was measuring the combined bone mineral density and bulk density, while ashing records mineral density alone (see above). No discussion of this is offered in the text. Butler and Chatters were able to use their results to interpret convincingly a number of North American prehistoric assemblages.

The contribution of this work to the field of taphonomy can hardly be disputed, since it demonstrated that density is as important a mediating factor in the survival of fish remains as it is for mammals. Perhaps the small size of the chinook salmon and

their ready availability are responsible for the authors' ability to procure and examine a comparatively large (but still not necessarily statistically robust) sample size. Also, the introduction of the hydrostatic weighing method of volume measurement was surely an improvement on the various displacement methods used by the earliest studies. However, the text is not clear on how the volume of each element is combined with the DEXA measurement to produce a volume density for each scan-site. Clarification is needed here before the methodology can be assessed properly.

6.2.9: Elkin 1995

The list of taxa for which bone density measurements are available was further expanded in 1995 by Elkin. In her work, Elkin drew largely on the work of Lyman (1984). She measured the skeletal remains of a variety of camelids (one vicuña, one llama and two guanacos – all adult) using photon densitometry. She looked at the mandible, atlas, axis, cervical thoracic and lumbar vertebrae, sacrum, ribs, scapula (glenoid and blade) carpals, pelvis, tarsals, astragalus, calcaneum, all three phalanges, and the proximal, distal and shaft parts of all of the long bones - including the metapodia of each animal (Elkin 1995 p30, table 1). No figures were provided for the shafts and the exact locations of each scan-site are not revealed). Elkin states that "Lyman's method of measuring volume density was followed as closely as possible" (Elkin 1995 p30). However, she recognized the shortcomings of Lyman's methodology regarding the conversion of linear density into volume density (outlined above) and in a second set of experiments attempted to improve upon Lyman's work by measuring bone volume independently by water displacement. The precise details of this new methodology are not fully explained, but involved the cutting of each element into three parts (proximal, distal and shaft) before immersing each of the parts in water in order to obtain a volume for the proximal, distal and shaft portions of each. This new methodology was shown, at least partially, to overcome the problem of the irregular shape of most bones. However, Elkin herself notes that the "coating of bones in order to prevent water intrusion into the pores, was not possible owing to the lack of an adequate coating material" (Elkin 1995 p31). This deficiency would result in the volume measurements being adversely influenced by bone porosity, and so would not be a true representation of bone "bulk" volume.

$$\text{Volume density} = \frac{\text{Linear density}}{\text{Volume of scanned part of bone} + \textit{some} \text{ air spaces}}$$

Elkin reports that multiple measurements on the same bone produced a variation of only 0.5%.

The contribution of Elkin's work to this field of study is clear: the addition of three new taxa to the list of animals for which density values are available served to increase the interpretative powers of zooarchaeologists (particularly those working in South America). Unfortunately, Elkin suffers the all too common disadvantage of having a small sample size. This is bound to throw doubt on the value of her results. Also, the failure to coat the sample in a non-absorbent material is a serious drawback. This flaw in the methodology means that the density measurements produced will not take into account variations in the porosity of the material. Consequently, small dense elements will potentially produce similar volume measurements to large porous elements.

6.2.10: Willey, Galloway and Snyder 1997

Until 1997 no attempt had been made to assess the density of human remains, with respect to their varying preservation in the archaeological record. The work by Willey, Galloway and Snyder (1997) attempted to redress this. The sample employed was comparatively large. Ten males and twenty-two females (all "contemporary", of known age – over 15 years – and of mainly European ancestry) were examined. The measurement technique was single photon absorptiometry. Linear density was converted to bulk density by dividing by bone thickness – as determined by caliper measurement at each scan-site. This is a replication of the methodology laid down by Lyman (1984) and contains the same drawbacks. As well as volume density, "density by circumference" was calculated by dividing linear density by the bone circumference/π at each scan-site:

$$\text{Circumferential density} = \frac{\text{Linear density}}{\text{Circumference at scan-site}/\pi}$$

Circumferential density is much the same as volume density, but rather than assuming that the bone has a rectangular cross-section, assumes that the cross-section is circular. It was shown in the text to be considerably more useful in predicting bone survival than volume density. The bones under investigation were the humerus, radius, ulna, femur, tibia and fibular. The scan-sites used were different from Lyman's. Each bone was scanned at 20%, 35%, 50%, 65% and 80% along the length of the bone – as measured in a distal to proximal direction. This choice of scan-sites deliberately

mirrored the recording system used on the Crow Creek archaeological site in south central South Dakota and so enabled a taphonomic examination of this particular site.

This study represents a considerable step forward in taphonomic investigations. Its most commendable aspect is perhaps in the detail in which the modern sample was recorded. Considerable attention was given to the assumptions on which the analysis was based, with all of the possible drawbacks being highlighted. Nevertheless, the success with which the method was able to predict bone survival at Crow Creek demonstrated that these assumptions were justifiable. The success of circumferential density over volume density in predicting bone loss was possibly a result of the bones having a roughly circular cross-section rather than a rectangular one, at each scan-site. It is regrettable that this was not tested by comparing the predictive power of the circumferential density of rounded elements and that of less rounded elements (eg femur versus scapula). Until such a test is carried out, it is only possible tentatively to conclude that the success of this investigation was largely due to the validity of the assumption that the cross-sections of the measured material were rounded. Willey *et al* also highlighted the fact that they were obliged to assume that their modern sample was indeed comparable to the archaeological sample and that diagenetic processes do not have any distorting effects on the relative densities of buried bones (pp517 - 519).

6.2.11: Lam, Chen and Pearson 1999

In their comprehensive paper Lam *et al* (1999) undertook density measurements of twelve adult skeletons (four wildebeest (*Connachaetes taurinus*), four reindeer (*Rangifer tarandus*), two Burchell's zebras (*Equus burchelli*) and two Przewalskii's horses (*Equus przewalskii*)). The specimens were of unclear origin, but each genus was represented by both wild and captive specimens. Since the presence of grease may result in inflated measurements of bone density (Dirrigl 2001 p818, Ruff and Leo 1986 p182) the authors were careful to select only degreased specimens. This obliged them to assume that the method used to degrease and deflesh the material did not "significantly alter the *pattern* of intra-skeletal bone density" (Lam *et al* 1999 p350). The scan-sites chosen were based on those specified by Lyman (1984 pp274 - 275). The technique used to measure mineral density was quantitative computed tomography (QCT). By using QCT, the authors were able to improve upon many previous studies by excluding any internal cavities (ie medullary spaces) when calculating the density of the material. They also calculated a parallel set of density values that did not exclude the effects of any medullary spaces. This enabled them to demonstrate that the assumption that bones

have a homogenous cross-section often employed when measuring bone density results in an underestimation of bone density at 40% of Lyman's scan-sites (Lam *et al* 1999 p352). Whether the exclusion of medullary spaces from the calculation of a bone's density is in fact desirable is debatable. This will be discussed in section 7.3.3.

In their paper, Lam *et al* provided an excellent comparison and assessment of some of the measurement methods used by other researchers (many of which are discussed in this section). Since they made use of the highly accurate technique of QCT, there can be little doubt that their results are reliable. However, QCT is an expensive technique. Although the sample size of 12 individuals is larger than that employed by some of the authors already mentioned, the use of a less expensive technique might have enabled an even larger sample to be examined. Lam *et al* (1999 p356) stress that any new attempts to measure bone density risk redundancy unless they focus on *intra-taxonomic* variability, which may be the result of variability in diet, sex, age, season of death or physical condition. This project will focus on the impact on bone density of age, but will also be able to address the effects of sex, breed, season of death and the preparation method used to deflesh the material.

6.2.12: Pavao and Stahl 1999

The research published by Pavao and Stahl (1999) expanded the list of taxa for which bone density data were available even further. These authors examined the skeletons of six lepirids (two adult specimens each of *Sylvilagus floridanus* and *Oryctolagus cuniculus* and an adult and an immature *Lepus canadensis*). Photon absorptiometry was used to determine the density of the bones. The experimental methods (including the choice of scan-sites) followed those proposed by Lyman (1984). The authors produced two sets of volume density values (VD). The first was calculated along the same lines as Lyman's VD values (by dividing each linear density value (LD) by the maximum thickness of the bone (Lyman 1984 p273)). However, Pavao and Stahl recognized that this would necessitate the assumption that the cross-sections of the material being measured were rectangular and would ultimately lead to an underestimation of the true volume density. In an attempt to overcome this, a second set of VD values was calculated. They assigned each scan-site a geometric shape that most closely approximated its profile. The areas of these shapes were computed, so that a closer approximation of the cross-section of each scan-site could be made. This *shape adjusted* volume density builds upon the use of circumferential density by Willey *et al*

(1997). However, in this case, the results produced are not restricted by the assumption that the cross-sections of the bones are circular.

Since the methods described above followed those used by Lyman (1984) (and others) so closely, many of the disadvantages already described are also applicable here. Not least is the difficulty and cost involved in gaining access to specialist scientific equipment. Also, the estimation of cross-section shape by Pavao and Stahl is bound to be somewhat subjective and will introduce its own potential bias (Pavao and Stahl 1999 p59). However, the method is bound to be an improvement on some of those employed previously. Perhaps the greatest criticism of the work of Pavao and Stahl (and one they acknowledge themselves) is the small number of animals that were examined. The authors warn that the data that they produced and conclusions that they drew should be viewed as being provisional due to the "small number of skeletons examined and the potentially great range of individual variations within each taxon" (p58). This project will demonstrate that this individual variation within each taxon is considerable and so the use of as large an experimental sample as possible is of paramount importance.

6.2.13: Stahl 1999

The method of producing shape adjusted volume density employed by Pavao and Stahl (1999 – above) was refined by Stahl (1999). In his analysis of camelid bone density, he examined the skeletons of three alpaca (*Lama pacos*), two llamas (*Lama glama)* and five *Lama sp*. Both male and female modern animals were examined. The scan-sites for which density data were produced were based on those proposed by Lyman (1984). Dual energy X-ray absorptiometry (DEXA) was used as the analytical technique and, where possible, the experimental methods described by Lyman (1984) were followed. Like many other researchers, Stahl encountered the problem of determining the cross-section of the scan-sites. As explained above, cross-section areas are required to enable linear density to be converted into volume density values. In this case, the cross-sections were drawn manually, using a carpenter's moulding tool and digital callipers. This enabled the "true" cross-sections areas (or a close approximation of them) to be measured. A computer, using a calibrated digital image of the hand drawn cross-sections enabled this measurement to be made.

This innovation was an improvement on many previous DEXA-based studies, because these often necessitated some assumptions regarding the shape of the cross-sections (Kreutzer 1992, Lyman 1984, Pavao and Stahl 1999, Willey *et al* 1997). In Stahl's study, the measurements used were, in theory at least, accurate representations

of the true area of the cross-sections of each scan-site. Stahl notes that his method is still prone to the underestimation of true bone density, because his cross-section diagrams were unable to establish the size and shape of medullary cavities or other heterogeneity within the bone. The importance of this factor in bone density studies will be discussed later (section 7.3.3).

Although the method used by Stahl was undoubtedly a considerable improvement on many previous methods, it still incorporated some potential for error. Firstly, no attempt appears to have been made to ensure that the technique of drawing the bone cross-sections was reliable. In a pilot study for this thesis, an attempt was made to draw bone cross-sections using the methods proposed by Stahl. However, the method was deemed too unreliable to be included in the final methodology for this project. Confirmation of the reliability of this aspect of Stahl's method through a repeatability study is clearly desirable.

Secondly, Stahl produced cross-section drawings of only one animal. These drawings and the cross-section areas derived from them, were applied to all of the individuals examined in his study. Consequently, this method was prone to errors whenever the animals being examined were of unusual size or skeletal morphology. This would be especially problematic if immature animals were to be examined. It seems that some assumptions regarding the cross-section area of the experimental material were still implicit in Stahl's method. Specifically, the shapes of all of the experimental material was assumed not to differ between individuals. The effect of this assumption on the results is likely to be slight when compared to the underestimation of bone density associated with many other studies.

The number of individuals examined by Stahl (n =10) was comparatively small. Consequently, the results produced are bound to lack the statistical reliability that might otherwise be desired. Furthermore, the practice of averaging density values from multiple individuals has the potential effect of masking inter-individual variability. This practice has been common in the previous studies discussed in this chapter, although, until the nature of inter-individual variability is understood, it should be avoided.

Although Stahl's study made a considerable contribution to both the understanding of bone density and to the appreciation of methodological issues involved in bone density measurement, it is not without some drawbacks. In addition to those mentioned above, the use of DEXA as a measurement method has already been noted as being somewhat expensive and inaccessible.

6.2.14: Ioannidou 2000

The third investigation into animal bone density to have been produced in 1999 was carried out by Ioannidou (2000). In her research, Ioannidou used photodensitometry to assess the bone density of two ox, one sheep and three wild boar skeletons. She also included in her analysis three immature pig skeletons and a collection of individual pig and sheep humerii and tibiae. These individual bones were intended to increase the sample size from which her data were obtained. Modern material was apparently used for all measurements. Ioannidou intentionally followed closely the experimental methods outlined by Lyman (1984), Elkin (1995) and Kreutzer (1992). The conversion of LD to VD followed the approach used by Lyman (1984). One of Ioannidou's main research objectives was to assess the impact of the age, sex and breed of an animal on its bone density. This was the first study that explicitly attempted to address the impact of these variables on bone density.

By largely reproducing the experimental methods set out by Lyman (1984), Ioannidou has incorporated into her study most (if not all) of the methodological problems and advantages discussed above (see section 6.2.5). Perhaps the main advantage is that her results can be confidently compared with those of Lyman and other similar studies. Importantly, Ioannidou notes that difficulty in securing access to the photondensitometer means that her sample had to be severely restricted. Although her sample size is larger than many discussed so far, she notes that, had it been as large as was originally intended, the conclusions she was able to draw would have had a "broader validity" (Ioannidou 2000 p53).

The aims of this project and that of Ioannidou (the investigation of variations in age, sex, breed etc. on bone density) are comparable. However, Ioannidou has demonstrated that a large experimental sample is required to achieve this satisfactorily. This project will examine as many individuals as possible.

6.2.15: Dirrigl 2001

The most recent study to be discussed here focussed on the density of modern bird skeletons. Dual energy X-ray absorptiometry was used to determine the density of the skeletons of eight wild turkeys (*Meleagris gallopavo*). Data were also produced for the densities of the bobwhite (*Colinus virginianus*), ruffed goose (*Bonasa umbellus*) and prairie hen (*Tympanuches cupido*), but remain unpublished. All material was prepared by the dermestid beetle method. Male adult birds only were examined. The methods described by Lyman (1984) were broadly followed, although, rather than using specific

scan-sites, Dirrigl adopted “regions of interest” (ROIs) as his basic area of measurement. ROIs tend to include a larger area of bone that Lyman’s scan-sites and are intended to overcome variations in bone morphology specifically associated with bird bone. Conversion of linear density into volume density was achieved by dividing LD by the average thickness of each ROI. Average thickness was estimated by dividing the sum of the maximum and minimum thicknesses of an ROI by two.

$$\text{Volume density} = \frac{\text{Linear density}}{(\text{Max thickness of ROI} + \text{Min thickness of ROI}) / 2}$$

Although this method of determining bone thickness shows an appreciation of the work of Elkin (1995), Willey *et al* (1997), Kreutzer (1992) and Pavao and Stahl (1999), its applicability has not been assured. The use of only two measurements to derive an average bone thickness is likely to be subject to errors caused by irregular bone shapes. Experimentation is required in order to ascertain the reliability of this aspect of Dirrigl’s method. Dirrigl’s research (2001) was thorough and well-considered. If the bone thickness measurements he used can be shown to be reliable, than the addition of these avian taxa to the list of animals for which bone density data is available will be extremely valuable.

This review of the methodologies of previous relevant investigations has highlighted a number of issues that must be considered when a methodology is being designed. These include the sample size, species and element selection and the ability for the data being produced to address the specific research questions of the investigation. Also, problems inherent in a number of methodologies have been highlighted – such as the need for accurate determination of the volume or thickness of a bone (whichever is appropriate). The issues raised by this section will later be drawn upon, to ensure that the methodology developed for this project is well suited to the research questions being posed.

6.3: The Available Measurement Techniques

The above section reviewed a number of specific investigations into bone density. This enabled issues of the material as well as the methodologies used by previous researchers to be addressed. This section will concentrate on the measurement

methods themselves, and will draw upon the literature that assesses the precision and accuracy of these methods.

The clinical research into osteoporosis has led to the development of a wide variety of methods of bone density measurement. These methods differ in their accuracy, precision, cost, and applicability to archaeological research. This section aims to review the analytical techniques that are most applicable to this project in particular. Consideration of the issues raised in a review of this sort will ensure that the choice of methodology used here is appropriate. Before this review is undertaken, it must be noted that there is little consistency in the names ascribed by various authors to the techniques described below. To avoid confusion, the nomenclature used by Brickley (1997) will be adopted here. It should also be noted that the accuracy and precision of statistics given in this section were originally obtained by different scientific and statistical techniques and so can act as a guideline only. Finally, no note will be made of a range of attributes of each methodology (eg the effective dose to which the patient is exposed during measurement and the problems posed by the presence of soft tissue) since these are of no relevance to the measurement of defleshed archaeological material.

6.3.1: Radiogrammetry

Radiogrammetry (or optical densitometry) requires little attention here, since it is primarily a technique for diagnosing and monitoring osteoporosis. The technique involves the measurement of cortical bone thickness from radiographs of one or more of a variety of (generally apendicular) skeletal locations (Barnett and Nordin 1960). As such, it does not measure trabecular bone at all. Neither does it provide an indication of bone density for any specific part of the skeleton. Instead, by comparing the cortical bone thickness with that of a healthy subject, a general indication of skeletal health can be extrapolated. Despite this, the technique has successfully been used by Horwitz and Smith (1990) to assess the skeletal health of modern sheep flocks.

6.3.2: Photodensitometry

This method also relies on radiographic examination. Instead of measuring the cortical thickness of an image, photodensitometry measures the opacity – or *optical density* – of the image (objects of higher radiodensity produce lower optical densities). The measurements are taken by measuring the intensity of light that has passed through the relevant part of the radiograph. By including a standard of known density (or, more often, an aluminium wedge of multiple steps – each of known thickness and density) it

is possible to produce measurements of optical density for a range of known relative densities (Farquharson *et al* 1997 p766). In this way the measurements can be calibrated and standardised. The results are usually expressed in arbitrary units. Naturally, large bones (being thicker) will produce higher photodensitometry readings than smaller, thinner ones, even if they are of the same density. Consequently, in the case of living subjects, this technique is only suitable for the comparison of data derived from a common scan-site, or for longitudinal studies. The problem of non-uniformity of thickness of scan-sites can be overcome in archaeological research, since in the absence of soft tissue, the bone thickness can be measured directly. However, the various attempts of archaeological researchers to overcome this problem have proved either inaccurate or necessitate the destruction of the bone. This method has the advantage of being relatively cheap, and requires little in the way of specialist equipment. According to Genant *et al* (1996 p708) photodensitometry has a precision of 1-2% and an accuracy of 5%. This is slightly better than the figures of 2% and 6% respectively returned by Cosman *et al* (1994 p35). Both precision and accuracy are subject to improvement in the absence of soft tissue – as is the case with most archaeological material (Yang *et al* 1994 p859).

6.3.3: Single photon absorptiometry

By passing a collimated beam of low intensity photons through a subject and measuring any loss of intensity of the beam after it has passed through the object, it is possible to calculate a sample's attenuation. The level of attenuation is dependent on the mineral content of the object. Researchers often take measurements of bone thickness or scanned area in order to produce results in g/cm^2 or g/cm^3 . This technique has been used widely by the archaeological community to produce a range of bone densities for a number of different taxa (Butler and Chatters 1994, Chambers 1992, Elkin 1995, Kreutzer 1992, Lyman *et al* 1992, Lyman 1984) (see section 6.2). However, as mentioned in section 6.2.5, measuring bone thickness alone will not take account of the irregular shape of the bones, or the presence of a marrow cavity in the bone's shaft. Consequently, this method is prone to systematically underestimate bone density (Lam *et al* 1998 p568). The precision and accuracy of this method are said to be approximately the same as in photodensitometry (1-2% and 5% respectively – Genant *et al* 1996 p708). A considerable drawback of this method is that it requires the use of relatively expensive and difficult to obtain scientific hardware.

6.3.4: Dual photon absorptiometry

This technique is similar to single photon absorptiometry, but instead of using a beam of photons of a single intensity, employs two photon sources (usually gamma photons of 44Kv and 100Kv – Brickley 1997 p40). This enables the measurement of sites with varying amounts of soft tissue cover, rather than being limited solely to appendicular sites where soft tissue coverage is minimal (as is the case for the two previously discussed techniques). Genant *et al* (1996 p708) and Mazess *et al* (1988 p159) agree that the precision of this technique is 1-3%, depending on the make of machine used. Genant *et al* records the accuracy as being 4-6% (p708), while Mazess *et al* simply note that the accuracy of dual photon absorptiometry is "excellent" (p158). The main advantage of this technique is that it enables the measurement of axial sites, which are more thickly fleshed. However, since archaeological material is rarely fleshed and the modern sample used in this project will similarly be defleshed, this advantage is barely relevant. Nevertheless, this fact did not prevent Ekenman *et al* (1995) electing to use dual photon absorptiometry in their study of medieval human skeletons. This technique still suffers from the drawback that it requires access to expensive medical hardware and that, except in the case of longitudinal studies and studies where similarly sized elements are to be examined, it is necessary to ascertain the cross-sectional dimensions of the sample.

6.3.5: Dual Energy X-ray absorptiometry (DEXA)

Dual energy X-ray absorptiometry is an improvement on dual photon absorptiometry. In this case, rather than using two isotope sources, a stable X-ray tube is used and the change in intensity of the X-rays is measured in order to ascertain the mineral density of the sample. Among the advantages of this method is a shorter scanning time and higher spatial resolution. Genant *et al* (1996 p708) note that the accuracy of this method is between 3-10%, depending on the scan-site. Turner *et al* (1995 p385s) returned precision values of between 1.4-4.3%, depending on the scan-site. This level of precision is in line with, although slightly lower than, that of Genant *et al* (1996 p708) who published a precision of 1-3%. The variation of accuracy and precision according to scan-site is probably the result of variation of the thickness of soft tissue cover over the bone being studied. Naturally, in defleshed specimens, this would be not be an issue. Another variable that has been shown to affect the precision of this method is the level of density being measured. The precision of DEXA is notably

higher when it is used to measure relatively high densities and falls as the densities of the bones being examined fall (Farquharson *et al* 1997 pp767 - 770).

Despite all of its advantages, DEXA still suffers from many of the disadvantages outlined above – namely, the problem of determining the bone cross-section and the difficulty in accessing the necessary equipment.

6.3.6: Quantitative computed tomography (QCT)

Computed tomography is a technique with numerous clinical applications. The application of concern here is the measurement of bone density. This is an application for which QCT's validity is "widely accepted" (in the case of vertebral trabecular bone measurement (Genant *et al* 1996 p710)). However, Brickley (1997 p41) warns, "there are still unanswered questions about the precision error of the technique". Brickley is not specific about the nature of these questions, but it is likely that she is referring to edge and beam hardening artefacts identified by Ruff and Leo (1986 p192). Genant *et al* (1996 p708) report that the precision and accuracy of this method are 2-4% and 4-15% for spinal measurements (again, dependant on the exact scan-site involved). These statistics improve to 1-2% and 2-8% for measurements of the peripheral skeleton. Ruff and Leo (1986 pp189-193) compared density values of defleshed samples generated by QCT with those measured directly (see below) and noticed a correlation of $r = 0.999$. They took this as indicative of the fact that, *when used on defleshed material*, QCT is capable of producing results of a very high quality.

QCT is able to create an image of the subject in three dimensions, thus overcoming the need to determine the sample thickness by means of a separate measurement. This contributes significantly to the accuracy of the method, rendering it considerably more accurate than the absorptiometry methods outlined above (Lam *et al* 1998 p554). This also has the desirable effect of rendering QCT more accurate than the previously discussed methods, because there is no longer the need to estimate the bone thickness (especially in bone shaft measurements, where the marrow cavity of the bone can only be accurately measured by cutting up – and so destroying – the bone (Lam *et al* 1998 p554)). The three dimensional images are produced by taking as many as 360 measurements of the sample at different orientations and digitally combining the data produced (Ruff and Leo 1986 pp182-183). QCT also has the advantage of being able to differentiate between the cortical and trabecular bone of the vertebrae. Unfortunately, the enormous cost of the equipment means that it is even more difficult to access than

that described already. It is most unlikely that archaeological research will be able to secure laboratory time for QCT when the clinical pressure for the hardware is so high.

6.3.7: Low angle X-ray scattering (LAXS)

This comparatively little used technique involves the bombarding of a sample with a collimated polyenergetic beam of X-rays. The equipment measures the intensity of X-rays of each wavelength that has been defracted by the sample by 5°. By plotting the intensity over the wavelength, it is possible to recognise minerals, and to calculate their quantities within the sample (since each mineral will defract X-rays of a specific wavelength by the angle of 5°), (Brickley 1997 pp148-149). This means that not only is LAXS capable of measuring bone mineral density, but it is also able to produce densities for specific minerals within the bone. In her 1997 thesis, Brickley noted that LAXS was still at the developmental stage. This is no doubt why Genant *et al* (1996) do not supply precision and accuracy statistics for this technique. However, Brickley herself recorded a correlation of $r = 0.84$ and $r = 0.93$ ($p < 0.001$) between LAXS and directly measured "Baseline Density" (Brickley 1997 pp232-234, later published in Farquharson *et al* 1997 p771) (see below).

The comparatively accurate results obtained from LAXS by Brickley and the technique's ability to differentiate between minerals are probably its greatest assets. However, the latter is of little use to a study into the relationship of bone density and archaeological durability until the contribution of specific minerals to the strength of archaeological bone has been determined (a task that is not within the remit of this project). Furthermore, as is the case for so many of the techniques discussed in this section, LAXS equipment is not yet widely available and so access to it is difficult.

6.3.8: Direct density measurement

A method that is often adopted in archaeological research could be termed "direct density measurement". This type of methodology was variously used by some of the pioneers in archaeological research into bone density (Brain 1969, Behrensmeyer 1975, Binford and Bertram 1977, Boaz and Behrensmeyer 1976). The apparent popularity of this type of method was probably due to its being relatively quick and cheap to perform. All of these pioneers used a variation on the method of dividing the weight of their sample by its volume (usually determined by measuring the volume of liquid displaced when the sample was immersed in water (see section 6.2.1 - 6.2.4).

Ruff and Leo (1986 p190) directly measured bone density by milling a sample into a rectangle, and dividing its weight by its volume (which was measured using callipers).

An alternative to this was used by Brickley (1997 p143) when she calculated trabecular bone density by weighing a sample before and after the removal of a known volume of bone and dividing the difference in weight by the volume of bone that had been removed:

$$\text{Density} = \frac{\text{Weight before removal of bone} - \text{Weight after removal of bone}}{\text{Volume of bone removed}}$$

No data are available for the precision or accuracy of these measurements, not least because these data would vary according to the exact experimental procedures followed. However, Brickley, and Ruff and Leo were sufficiently satisfied with their techniques to use data produced by direct measurement as "baseline" or "true" density, against which the results of optical densitometry, DEXA and LAXS (Farquharson, 1997) and QCT measurements (Ruff and Leo, 1986 – see above) could be compared. The results of these comparisons are summarised in Table 6.1.

Measurement Method	Correlation with Directly Measured Density	Reference
Optical Densitometry	r = 0.64 (femoral neck) r = 0.85 (vertebral body)	Farquharson (1997) p771
DEXA	r = 0.64 (femoral neck) r = 0.74 (vertebral body)	Farquharson (1997) p770
LAXS	r = 0.84 (femoral neck) r = 0.93 (vertebral body)	Farquharson (1997) p771
QCT	r = 0.999 (femoral shaft)	Ruff and Leo (1986) p190

Table 6.1: Summary of the correlation between directly measured density and non-invasive techniques.

It is apparent from this table that QCT is the most reliable non-destructive means of measuring bone density, while DEXA is the least. A note of caution regarding this interpretation of the data is that each study employs a specific set of experimental criteria from which it produces its results. It is quite possible that under a different set of experimental conditions, optical densitometry will provide the lowest correlation with directly measured density. This is a reflection of the fact that each methodology has a set of circumstances to which it is best adapted. However, it is not unreasonable to take

the data laid out in table 6.1 as a valid guide to the comparative accuracy of the methods specified.

A considerable drawback of the direct measurement of bone density is that it is invariably destructive and so cannot be carried out on valuable archaeological or reference material, except in exceptional circumstances.

This assessment of the main measurement techniques has raised a number of issues that must be incorporated into the method design of this project. The precision and accuracy of the chosen technique are of clear importance. Also, the cost and availability of the equipment required must be taken into account. These and other issues will be summarised and incorporated into the methodology of this project, below.

6.4: Summary and Experimental Design

The previous studies and measurement techniques described above addressed a series of issues that should be considered when designing a method for the measurement of the density of animal bones. These issues ensure that the data produced were reliable and were fully applicable to the research questions being posed. These questions will be summarized below, before the method to be employed here is described in full detail.

6.4.1: Sample size

One of the recurring features of the discussion in section 6.2 is the need for a sufficiently large sample. The majority of the previous investigations employed relatively small samples and so any patterns that could be identified within the data were not statistically robust. It is the aim of this project to analyze as many individuals as possible. Unfortunately, this aim is likely to be achieved at the expense of the range of variables (age, taxa, breed etc) that can be built into the analysis. However, it is much easier to justify the production of reliable data with a small range of variables, rather than the production of data that cover a huge range of variables, but remain unreliable.

6.4.2: Taxon choice

Each of the methodologies described in this section presented the gathered data with a specific set of research questions. In each case, the taxon chosen was the one that was best suited to address these questions. For example, Brain's (1969) use of goat and Willey *et al*'s (1997) use of human as sample material were natural choices, since they

were looking at assemblages of ethnographic goat and archaeological human remains respectively.

6.4.3: Element selection

Previous investigations have focussed on a variety of skeletal elements, ranging from just the proximal and distal halves of four long bones (Brain, 1969) to multiple scan-sites on almost every element of the skeleton (Kreutzer 1992). These studies measured the properties of bones that were most applicable to the specific research questions, within practical constraints. It is the intention of this study to examine the maximum range of elements, while producing only data that will be of considerable use in archaeological interpretation. The four criteria laid down by Lyman (1984) will be employed here for element selection (see section 6.2.5).

This project aims to assess the variation in bone density as an animal ages. Consequently, there is little advantage in measuring the density of material that cannot reliably be aged in the archaeological record.

Other bones that need not be included in the sample are those that cannot reliably be identified in the archaeological record. Density data on bones that cannot normally be assigned a taxon and element will be of little use in archaeological interpretation. Furthermore, the faunal recording system employed at Çatalhöyük does not record the taxon of certain elements. These elements (vertebrae and ribs) are simply recorded by the size category of the animal. Consequently, data on the density of these elements will be of little use since it will only be able to be applied to “sheep sized” archaeological material which might include, for example, bones from dogs or young pigs.

By minimizing the elements that are to be measured to the ones that are most useful and able to answer the specific archaeological questions being posed, it will be possible to maximize the number of individuals that are examined.

6.4.4: Scan-site selection

The criteria for the selection of the specific scan-sites were similar to those to be considered when selecting the elements that were to be measured. Namely, the four criteria laid out by Lyman (1984) (see section 6.2.5), and the ability of the data to answer the specific archaeological questions. Perhaps the most important issue here is that the scan-sites must coincide with parts of the bones that are specifically recorded as being either present or absent by the Çatalhöyük recording system. This criterion

influenced the selection of scan-sites by Willey *et al* (1997), who tailored their scan-sites to be directly compatible with the recording protocol used on the Crow Creek archaeological site.

Another important consideration is that the scan-sites finally selected must be on or related to identifiable bone "landmarks", so that they can be positioned accurately and reliably. The scan-sites selected according to these criteria are described in section 7.1.3 and in more detail in appendix A.

6.4.5: Material source

It is necessary to decide whether the sample material to be used is to be comprised of modern or archaeological material. This is a straightforward decision. All of the previous studies described above employed modern material. This is because archaeological material will have undergone a number of diagenetic and other processes that have the potential to alter bone density to an unknown degree. By using archaeological material, a poorly understood and unquantifiable source of error is being introduced. In addition, archaeological material will not have a known age at death, or any data on breed, sex or life history associated with it. As such, it will be of little or no use to this project.

A detailed description of the material used in this project (taxa, element, scan-site and material source) is given in section 7.1.

6.4.6: Measurement method

In addition to precision and accuracy, the assessment of the techniques described in section 6.3 highlights one factor above all others that limits their suitability for this project: the cost and availability of the hardware required. This is of particular importance considering the need to measure a large sample and the aim of this project to establish a methodology that can be easily adopted by other researchers at a later stage. Even if access to one of the more advanced measurement techniques could be secured and financed, it would be most unlikely that sufficient laboratory time could be afforded to enable measurements of a very large sample to be made. Also, access to the equipment for other researchers who might want to add to the data set produced here could not be guaranteed. Consequently, it is necessary to turn to one of the less advanced methodologies to provide a basis for the technique to be employed here, namely, photodensitometry.

Few of the advantages of the more advanced techniques are applicable to this project, since they are intended to measure live or fleshed material, while the subject material here will be modern defleshed animal bone. In addition, the assessment of the precision and accuracy of the various techniques, although not without fault, does suggest that photodensitometry is comparable in its ability to produce reliable results. The details of how the density measurements were taken are described in section 7.3.

This chapter has reviewed the previous archaeological investigations of bone density as well as the measurement methods available to the researcher. The various merits of each methodology have been noted and drawn upon in order to outline a methodology that is best suited to fulfilling the specific requirements of this project. The methodology outlined here will be described in full in the next chapter.