Chapter 3 – Destructive Processes and their Mediating Factors

The following pages will present the main taphonomic factors that are responsible for the analytic absence of bone from archaeological sites. It will become apparent that many of the effects of taphonomic processes are mediated largely by the density of the bone on which these processes are acting. Some processes will be shown to be more difficult to predict than others, although in all cases bone density plays a central role. This information justifies the use of bone density when attempting to assess the impact of these processes on an archaeological bone assemblage.

3.1: The Structure of Mammal Bone

The following section (and later sections in other chapters) will occasionally refer to both the microscopic and macroscopic structure of bone. For this reason, it seems appropriate at this stage to include a brief description of the relevant aspects of bone structure. The description below examines the structure of bone, first at the smallest scale and then at successively lower resolutions until the macroscopic structure of bone is described. In this way the structure of bone will be examined at all scales.

Bone can be described as a tissue that consists of approximately 70% inorganic material (mostly hydroxyapatite – $Ca_{10}(PO_4)_6.2OH$) and about 30% organic matter (mostly collagen). The hydroxyapatite crystals are imbedded in a matrix of collagen fibres. The exact chemical composition and organisation of these constituents of bone partly determine its mechanical properties and susceptibility to diagenetic processes (as well as its radiodensity).

The basic building block of bone is the collagen fibril (with its associated hydroxyapatite crystals). These fibrils can be arranged in random orientations to form woven bone. Woven bone is usually found in developing skeletons and in fracture calluses. In more mature or healthy bone, collagen fibrils form lamellar bone. In this bone the fibrils form alternate layers (or lamellae) where each layer consists of fibrils that are organised in distinct orientations. The variation in fibril orientation between different lamellae has been shown to determine some mechanical characteristics of bone (see section 4.2.5).

Lamellar bone appears in the skeleton in three distinct forms. Firstly, it can extend, uninterrupted, in all directions for several millimetres (for example, around the circumference of mammal long bones). Secondly, it can combine with woven bone, in alternate layers, to form laminar bone. This type of bone is associated with rapid bone growth. Finally, lamellae can form in concentric layers on the inside of tunnels produced by osteoclasts (the cells responsible for bone absorption found naturally in the skeleton). The concentric rings of lamellar bone that are formed are known as Haversian systems, and combine to form Haversian bone. Each Haversian system in Haversian bone contains a blood vessel at its centre and is surrounded by a cement sheath. Haversian bone is subject to a constant regime of remodelling and renewal throughout the life of an animal.

At the lowest level of resolution, bone can be divided into cortical (or compact) and trabecular (or cancellous) types. Cortical bone has a relatively high density (which is determined largely by microscopic pores in the bone structure). It normally forms the shaft (or diaphysis) of a bone. Trabecular bone consists of a complex system of interlocking bone struts and plates. It is much less dense than cortical bone and its density is determined largely by the number and thickness of bone struts and plates (compared with the non-bone material between them). Trabecular bone is generally found at the ends (or epiphyses) of long bones.

This description of the structure of mammal bone is summarised in figure 3.1.

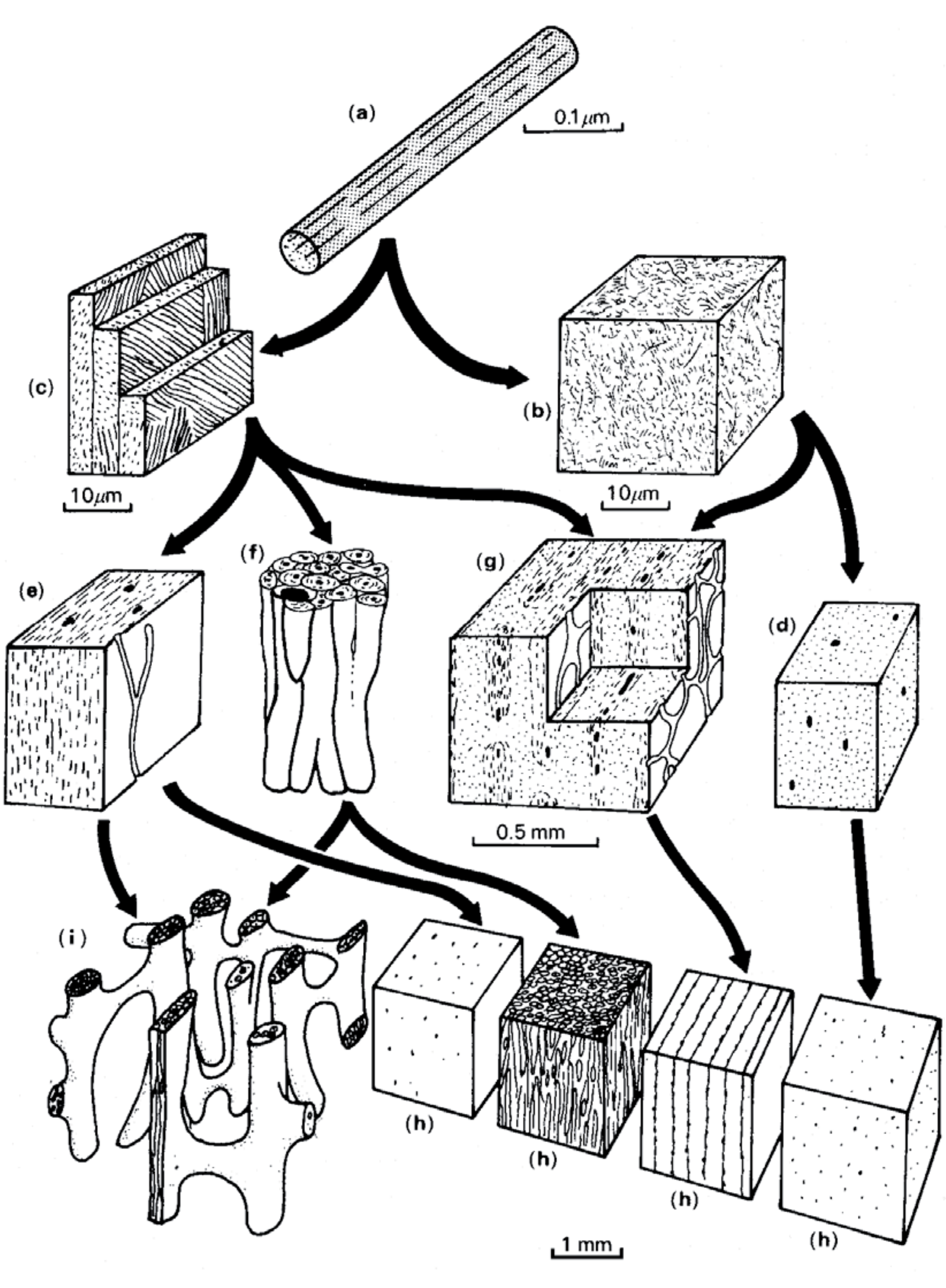

Figure 3.1: Showing the structure of mammalian bone at different scales and levels of organisation: a, collagen fibril with associated mineral crystals; b, woven bone, with collagen fibrils randomly arranged; c, lamellar bone, with separate lamellae consisting of collagen fibrils orientated in different directions; d, woven bone at the next level of organisation; e, lamellar bone at the next level of organisation; f, Haversian systems making up Haversian bone; g, laminar bone; h, cortical bone types (at the next level of organisation) consisting of lamellar, Haversian, laminar and woven bone; i, trabecular bone consisting of lamellar or Haversian bone types. From Lyman (1994 p75 fig 4.2).

This description of the structure and organisation of bone is not intended to be comprehensive. Instead, it aims to introduce some of the terms and concepts that will be referred to later in this project. A more complete description of the structure of mammalian skeletons can be found in Currey (1984).

This section has demonstrated that bones can vary in a range of attributes at a number of different scales. The chemical and physical organisation of bone material can change on either a microscopic or macroscopic level. An attribute of bone that is of particular interest to this project is that of bone density. It is therefore appropriate at this early stage to ensure that the concept of bone density is clearly defined.

3.2: "Bone Density" Defined

It is perhaps surprising that "bone density" is a very difficult term to define. Chapter 6 will describe a wide range of measurement methods, each of which has been shown to be measuring a slightly different variable. Strictly speaking, density is the ratio of mass to volume. However, bone is a porous material and so a distinction must be made between *true* density and *bulk* density. The former is the density of the bone material itself (exclusive of any air spaces) while the latter refers to the bone, or part of bone, as a whole (the volume of air spaces being included in the calculation). It is also necessary to differentiate between these variables and porosity, and specific gravity (Lyman 1984 pp264 - 265). Further types of density include radiodensity (the ability of an object to absorb X-rays) and bone mineral density (referring to the amount of mineral substance contained within a bone).

A further complicating factor is that different researchers employ different nomenclature for the same variable. The medical literature for example tends to use the term "apparent density" where the archaeological literature would use "bulk density". Also, the term "density" used by many researchers is in fact a combination of more than one of the variables described above. For example, Brain (1976) attempted to measure specific gravity, although he was only successful in measuring some hybrid of true and bulk density (Lyman 1984 p266). Indeed the bone "density" values experimentally produced by this project are in fact a hybrid of radiodensity, bulk density and bone morphology.

Against this background of confusion and non-standardisation, it is not surprising that "bone density" remains practically undefinable. Rather than add to the confusion, this project will follow the lead of Lyman (1984 p265) who simply used the term "density" to describe all of these variables, unless a specific definition was necessary or useful. This is possible because all types of density measurements as described here have in common the fact that they are useful in predicting the likelihood that a bone will survive destructive forces. To this end, "density" as used here could be taken to imply "robustness".

3.3: The Primary Taphonomic Processes

This section will address the impact and factors that mediate a wide range of taphonomic processes. Central to this discussion is the availability of different bones to each process. It should not be assumed that each taphonomic process will act on entire skeletons. The actions of each process will often be limited by the activities of humans. The availability of bones for gnawing by dogs or trampling, for example, will depend largely on the discard activities of humans. The need to consider human activity while investigating taphonomic processes introduces an extra cultural dimension into the processes. Predicting or modelling this cultural dimension is problematic. However, although it may not be possible to determine which bones were available for taphonomic destruction, the attributes of the material most likely to survive are well established. The separation of human and non-human processes is central to much archaeological interpretation.

Each taphonomic process will be discussed below in turn.

3.3.1: Weathering

Among the more researched taphonomic processes is that of bone weathering. This involves the gradual natural breakdown of bone, rendering it fragile and prone to destruction. Weathering is a process that begins at the moment of an animal's death, and continues (albeit at vastly different rates) whether it is exposed on the ground's surface, buried, or even in a museum cabinet (Lyman and Fox 1989 p294). Weathering is normally associated with bone that is exposed to the elements, on the ground's surface. The weathering of buried bone is much slower and will be discussed under "diagenesis" (below). Considerable effort has been spent in attempting fully to understand the processes by which bone undergoes weathering on the ground's surface. The factors controlling weathering, how it proceeds, how it might be recognised and its interpretative usefulness have all been discussed at some length.

Following the death of an animal, its bones will begin to show signs of chemical degradation and, in particular, the weakening of the bonds between the bundles of collagen fibrils. The process begins on the exposed surfaces of a bone and, in time, progresses into the inner bone substance (Bromage 1984 pp164 - 166). This is evident in the appearance of characteristic longitudinal cracks, which follow the direction of the collagen bundles. The result is that the bone is structurally weakened and so more prone to destruction by mechanical force.

The degree to which a bone has been weathered is usually assessed by the naked eye (diagenesis normally being assessed at the microscopic scale). Behrensmeyer (1978), established a means of assessing the impact of weathering on any particular bone by macroscopic examination. This study is still extensively used today. By examining a large amount of material recovered from the surface of the Ambesoli national park, Kenya, she noted that very few bones of "weathering stage 5" (the most weathered category) were recovered during her field studies. The implication of this is that, by the time a bone reached this stage of degradation, it was unlikely to survive archaeologically.

Miller (1975 p217) claimed that weathering is the result of the "effects on bone of saturation, desiccation and temperature changes". This largely environmental characterisation of weathering was repeated by Behrensmeyer (1978 p159), who noted the importance of microenvironmental as well as the more general habitat and climatic conditions. Numerous other researchers have also added weight to this observation (Andrews and Cook 1985 pp668 - 669, Brain 1967 p97, Cook 1986, Lyman and Fox 1989 pp297 - 299). Given the undoubted importance of environmental factors in determining the rate of weathering of bone, it is unfortunate that Lyman must remind us that:

> We still do not know the spatial scale at which microenvironmental variation will create *significant* variation in weathering rates; that is, we do not know how far apart two bones must be (assuming that they are of the same element and the same taxon) in horizontal space to ensure that they occur in depositional microenvironments that are sufficiently different to cause one of them to weather significantly faster that the other (Lyman 1994 p363).

This situation is not helped by the fact that the environment itself consists of a myriad of variables (eg temperature, vegetation, and moisture) whose interactions and impacts on weathering rates are poorly understood.

In his statement, Lyman touches on another important factor mediating the extent to which a bone is likely to be weathered. The need for the assumption that the bones in question are of the same element and taxon is based largely on the fact that bone density (which is known to vary between element and taxon) is of prime importance (Behrensmeyer 1978 p160, Gifford 1981 p417, Lyman and Fox 1989 p297, Todd *et al* 1987 pp68 - 70). Again, little is known about the exact effects of density on a bone's weathering rate, although Behrensmeyer (1978 p152) notes that "small compact bones such as podials and phalanges weather more slowly than other elements of the same skeleton". The relatively high porosity of low density bones means that they will exhibit a relatively high surface area to volume ratio. Since weathering begins on the exposed surfaces of bones, low density bones would therefore be expected to be more prone to this destructive process. Unlike the microenvironment, density is a relatively easily quantified variable. Consequently, data on bone density are likely to be most useful in assessing which bones are more likely to have been weathered to such an extent that they do not survive archaeologically.

A further relevant variable is bone size. Behrensmeyer (1978 p160 and 1982 p217) has suggested that smaller bones might be most rapidly weathered and so be removed from the archaeological record more rapidly than their larger counterparts. The reasons for this are uncertain: it might be because smaller bones have a higher surface area to volume ratio. Alternatively, smaller bones might require less fragmentation before they are rendered unidentifiable.

The last major factor governing bone weathering is time. The basic premise is that the more time between the death of an animal and the recovery of its remains, the more weathered it will become. This is only true in the case of bones that are lying on the ground surface, since buried bones weather at such a slow rate that they are considered to be comparatively stable. The relationship between weathering stage and time has been borne out by the strong positive correlation that has been identified between the maximum weathering stage recorded on a skeleton and the years since that animal's death (Behrensmeyer 1978 p157). Lyman and Fox (1989 pp299 - 308) explored this variable in some detail and highlighted some of the complexities often overlooked in the literature. These include the issues of the re-exposure of buried bones and the variable lag time between the death of an animal and the burial of its bones; both of which will have an effect on the weathering stage of archaeologically recovered bones that might not be apparent at first.

Weathering is a taphonomic process that results in the modification and, potentially, eventual absence of bone from archaeological sites. It is mediated, to a greater extent, by the microenvironment, the size and density of the bones, and the length of time over which the weathering processes act.

3.3.2: Gnawing and digestion

Sometimes, bones recovered from archaeological sites display evidence of having been gnawed. Animals and humans are capable of destroying bones by gnawing them. If this bone destruction is likely to lead to bias in the element frequencies of an assemblage, then these effects must be recognised and accounted for. Otherwise there is some potential for misinterpretation of the archaeological data. This section will address the aspects of gnawing that are likely to lead to bias in the archaeological record: namely, the dispersal and destruction of bone by gnawing. The destructive effects of digestion will also be addressed. This section will focus on the effects of carnivore gnawing, although attention will also be given to the gnawing of bone by ungulates and rodents. In addition to the movement and destruction of bone, gnawing frequently results in the production of "gnaw marks" on the bone's surface. However, this aspect of the process does not itself lead to bone bias and so is of limited relevance to this project. Gnaw marks are discussed comprehensively by Lyman (1994 pp205 - 216 and references therein).

3.3.2.1: *Bone dispersal by gnawing*

The subject of gnawing has also received considerable attention in the literature. Bones may be gnawed by a variety of animals (eg domestic and wild canids, rodents, herbivores and humans) for a variety of reasons and may produce more than one observable effect. One effect of scavenger or predator action on assemblages is bone dispersal. Considerable effort has been invested in various attempts to identify and understand the effects of animals moving bones around. They may do this as a result of food procurement (Kent 1981 pp369 - 371), maintenance of tooth condition (Andrews 1990 p7, Brain 1981 p109), or more obscure reasons (such as Morlan 1983 p216). The ultimate aim of the above studies was the ability to recognise and account for biases in the archaeological record brought about by such behaviour. Research has attempted to identify the main factors that control which bones are moved by each bone accumulator, and how far they are carried before finally being deposited. In the case of carnivores, the nutritional pressure acting on the accumulator is of prime importance. Stallibrass (1984 p267) was not the first to note that it is the meatiest bones (those with the highest MGUI – modified general utility index) that are ravaged first. Only after these bones have been gnawed will the carnivore turn its attentions to the less nutritionally valuable elements. The antithesis of this was observed when, in the total absence of competition, and the abundance of available food, a domestic dog involved in a gnawing experiment showed no interest whatsoever in the broiled bones that had been presented to her (Stallibrass 1990 p158). The literature is notably devoid of any specific references to exactly *how* carnivores (or other animals) might change the spatial patterning of bone assemblages, or how far different taxa are likely to transport these bones. Stallibrass (1984 p267) commented that it is not unusual for dogs to remove bones from their depositional context and carry them to caches in secluded areas in the urban environment, such as alleyways. However, this unsupported comment does not help archaeologists to use the spatial distribution of faunal material in order to identify and assess the impact of scavenging animals on an assemblage.

3.3.2.2: *Bone destruction by gnawing*

The destruction of bone through carnivore gnawing has received considerable attention in numerous well known studies. Possibly the most notable of these is the work variously presented by Brain (1967, 1976, 1981) in which an assemblage of goat bones was fed to domestic dogs and the element frequencies of the surviving material was recorded. Brain noted that the skeletal parts that were most resistant to gnawing by the dogs were also those with the highest bone density. Although Brain's original methodology is open to criticism (see section 6.2.1), his findings have not been disputed. Indeed, many authors have subsequently confirmed his original conclusions (Andrews and Evans 1983, Binford and Bertram 1977, Bonnichsen 1973 & 1979**,** Cruz-Uribe 1991, Haynes 1991, Kent 1981, Payne and Munson 1985, Stallibrass 1984 & 1990).

The factors that control whether a particular bone is likely to survive the attentions of a carnivore divide into two types. These are: a) the probability that a bone will be gnawed at all, and b) its ability to withstand the mechanical forces associated with gnawing. These two factors will be discussed separately.

It is first necessary to address whether or not a bone, having been deposited, is likely to be gnawed. Assuming that the gnawing is the result of food procurement, then an important factor here is (as in the case of transport by carnivores, noted above) the nutritional value (the combined value of the meat, grease and marrow) of the bone. The more nutritionally valuable parts of the skeleton have been observed to be preferentially consumed by carnivores (Hill 1975 p254, Stallibrass 1984 p267). This rule does not always apply: in the case of very small taxa, the *whole* animal will consumed irrespective of the nutritional value of its component parts (Andrews and Evans 1983 p291). Notwithstanding, it follows from this that in times of nutritional stress carnivores are more likely to try to take advantage of less nourishing parts of the skeleton which they might otherwise have ignored. Under such conditions, it is therefore conceivable that the pattern of destruction of a carcass will be more extensive (Stallibrass 1990 p161, Kent 1981 p370). Importantly, such times of nutritional stress are likely to be seasonal in nature. A less obvious mediating factor is that of the treatment of the bones before they are scavenged by (or fed to) the carnivore (Kent 1981 p369). Also, the individual tastes of the carnivores involved are likely to have some effect on the pattern of any scavenging. Stallibrass (1990 pp158 - 161) cites an example of a gnawing experiment in which the carnivore (a domestic dog named “Sappho”) showed no interest in the material that she was given to gnaw. This apparent apathy was interpreted as “personal whim” or a “temporary lapse in health” (Stallibrass 1990 p161). A further anecdotal example which demonstrates the potential influence of this factor is provided by Morlan (1983 p259) who describes two types of marrow that he had eaten himself. He found one type (from the humerus) distasteful, while the other (from the femur) was reported as being quite appetising. Presumably, if a carnivore exhibited this variation in personal taste, it would affect its treatment of the various parts of a carcass. This is summed up by Andrews and Evans (1983 p289) who note that an accumulation of small mammal bones is likely to “reflect the predator’s tastes and abilities more than the original mammalian community”.

Having addressed the factors that govern the likelihood that any particular bone will be the subject of a carnivore’s attentions, it is now necessary to assess which factors affect the ability of the bone to survive such attentions. In his original study in 1967, Brain correlated the element frequencies in his scavenged assemblage with the density of the bones themselves. This observation has been confirmed by Andrews and Evans (1983), Binford and Bertram (1977), Bonnichsen (1973 & 1979), Cruz-Uribe (1991), Haynes (1991), Kent (1981), Payne and Munson (1985) and Stallibrass (1984 & 1990). Stallibrass (1984) has interpreted preferential destruction of juvenile sheep bones by carnivore gnawing as being the result of their lower density. Such is the consensus on this subject that the importance of density in this context cannot be doubted. Additionally, the weathering stage of the bones being gnawed has been suggested as being of some importance here. More weathered bone is less likely to survive the destructive effects of gnawing (Cruz-Uribe 1991 p477), although it may be less likely to be gnawed by carnivores, since it will be less nutritionally valuable.

3.2.2.3: *Bone destruction by digestion*

Andrews and Evans (1983 p303) have suggested that the bones of small mammals may be protected from the effects of digestion by being enveloped in a layer of acid resistant fur while in the gut of the predator. They have also claimed that bone size is an important factor and that, in the case of small mammals being predated by birds of prey, it is the smaller bones that are more likely to survive the mechanical and chemical forces of consumption and digestion. Conversely, Haynes (1983 p109) reports on the somewhat extreme example of elephant bones that, he explains, are practically indestructible through gnawing. The importance of the size of a bone, or bone fragment, is apparent since only bones of less than a certain size (usually 1-2cm in length and never longer than 5cm) are likely to be swallowed by dogs. Bones larger than this are unlikely to be subjected to the further destructive forces of the predator’s stomach acids (Payne and Munson 1985 p34). Naturally, less dense bones will be more prone to being broken up into fragments small enough to be swallowed and so density is important here also. Also, the taxon of the carnivore is equally relevant, since small carnivores will generally be more limited in the size of bone fragment that they can swallow.

This might be an appropriate point to mention the importance of the taxon of the carnivore predator. A great deal of research into gnawing has focussed on the problem of identifying exactly *which* carnivore is responsible for any given assemblage (often the focus of research has been towards differentiating between animal and human collected assemblages). However, the use of bone frequencies alone has proved unsuitable for this. Instead, researchers have been obliged to refer to the types of breakage of, and marks on, the bones themselves. Since gnaw marks and breakage patterns do not themselves lead to the analytical destruction of bones, these aspects are of limited relevance here.

3.2.2.4: *The destructive effects of ungulate and rodent gnawing*

This discussion has so far focussed on the actions of carnivores, largely because carnivores are the most common gnawing agents to have been identified at Çatalhöyük. However, rodents, humans, herbivores and other animals have been identified as potential gnawing agents. The reasons for these animals gnawing bones are various and not always fully understood. Research into the nature and effects of these gnawing agents has been slight (especially in the case of human gnawing). However, some relevant literature does exist.

Nutritional factors have been implicated as the reason that ungulates sometimes gnaw bones (Brothwell 1976 p182, Johnson and Haynes 1985 p366). However, bone gnawing is suspected to fulfil a mineral rather than a calorific deficiency and so the bones most likely to receive this type of attention will not necessarily be those with the greatest MGUI (as might be the case for carnivore gnawing). The marks left by ungulates on bones that they have gnawed have been variously described (Brothwell 1976 pp180 - 181, Gordon 1975 pp124 - 128). However, little attempt has been made to assess the impact of this process on the element frequencies of an assemblage. Greenfield (1988 pp476 - 478) has demonstrated that pigs are capable of completely removing bones from the archaeological record through gnawing. He suggests that the factors that govern a bone's susceptibility to destruction by this process include its size, density and pre-gnawing treatment (ie had it been cooked before it was gnawed?). These factors are much the same as those associated with carnivore gnawing. Indeed, Greenfield (p476) concluded that the element frequencies of his experimentally produced pig-gnawed assemblage are similar to those shown to have been produced by carnivores. Much more experimentation is needed in this area before firm conclusions regarding the potential for ungulates to shape bone assemblages can be reached.

Other non-carnivores known to gnaw bones are rodents. Rodents engage in this activity in order to maintain the condition of their constantly growing incisors. Rodent-gnawed bones can be recognised by the parallel shallow scrape marks produced by these animals on the bone's surface. Again, since the reason for rodents gnawing bones is rarely nutritional, the MGUI of each element has little bearing on which parts of the skeleton are likely to be gnawed. Instead, the size of a bone has been considered as being important (Brain 1980 pp119 - 120, Hockett 1989 p33). Brain (1980 p123) has suggested that porcupines preferentially gnaw weathered bones. Rodent gnawing rarely results in bone destruction. Instead, bone transport is more frequently observed. Bone assemblages that are known to have been gnawed by porcupines show no signs of being structured according to bone density (Brain 1980 p119).

The analytical destruction of bones by carnivores relies largely on a combination of two factors. First is the likelihood that they will receive the attention of the carnivore in question. This can be approximately modelled with reference to the nutritional value of the bone and the nutritional stress under which the carnivore is living. Second, it is necessary to assess the bone's ability to withstand the actions of the carnivore. This relates to a greater extent on the size and density of the bone, as well as on the taxon of the carnivore in question. In the case of non-carnivores, the factors that affect the impact of gnawing on element frequencies within an assemblage are less clearly understood, although the size and (in the case of ungulate gnawing) density are likely to be important.

3.3.3: Trampling

Following deposition, bones and bone fragments that are laying on the ground surface are prone to being trampled by both humans and animals. This process is capable of destroying bones through mechanical action as well as by removing them from the archaeological catchment area by either horizontal or vertical displacement (Gifford-Gonzalez *et al* 1985 pp808 - 811, Olsen and Shipman 1988 p536). Trampling also affects faunal material by abrading it (Andrews and Cook 1985, Behrensmeyer *et al* 1986, Fiorillo 1989, Olsen and Shipman 1988). Although abrasion does not itself destroy bone, it may be used to identify assemblages which have suffered loss of material by trampling.

One of the variables that control the horizontal movement of a trampled assemblage is the depth of the bone below the subsurface of the ground. The deeper a bone is buried, the shorter the horizontal distance it will move (Gifford-Gonzalez *et al* 1985 pp808 - 809). It is therefore apparent that the factors controlling vertical displacement will have an indirect impact on horizontal displacement. Olson and Shipman (1988 pp536 - 537) report that the compaction of the substrate is an important factor that regulates vertical displacement. They suggest that a loose or soft substrate will enable the bones to be buried relatively rapidly, thus protecting them from subsequent movement. Vertical movement (both upward and downward – Olsen and Shipman 1988 p537) is also to a greater or lesser extent dependant on the intensity of trampling, the depth of the bones below the ground surface prior to trampling (Gifford-Gonzalez *et al* 1985 p816), as well as the size and shape of the bone. Small bones, or those with a relatively small surface area, have been observed to be buried most easily (Gifford 1977 p183) while the largest bones are more likely to be stepped around and so be quite unaffected by trampling (Lyman 1994 p379).

That trampling is capable of destroying bones is of little doubt (Andrews 1990 pp7 - 10, Haynes 1991 p253). The susceptibility of bone to the forces of trampling is, like horizontal and vertical displacement, also partly affected by bone size and shape. Yellen (1991b p165) has suggested that more spherically shaped bones are more durable (although this remains to be confirmed by other studies – Lyman 1994 p380).

Perhaps of more importance here is the overall condition of a bone when it is trampled. Myers *et al* (1980 p487) observed that weathered bone was much more prone to the effects of trampling than fresh bone. If this is the case, then the factors that mediate bone weathering will also indirectly control the impact of trampling. Irrespective of the weathering stage of a bone, its density will also control its ability to survive the destructive effects of trampling. Chapter 3 will demonstrate that dense bones are far more able to withstand the mechanical forces involved in destructive processes such as trampling than material of a lower density. There is therefore both a direct and an indirect relationship between a bone's susceptibility to trampling and its density.

It is apparent that the trampling of an assemblage is variously mediated by the size, shape and condition of the bones (or bone fragments) comprising the assemblage, as well as the composition of the substrate on which the material is originally deposited. This information is most useful to the archaeologist when trying to assess the impact of this process and trying to account for the absence of certain bones, or classes of bones, from any particular assemblage.

3.3.4: Butchery

This is an anthropogenic process that has received substantial attention from numerous authors. However, the focus has tended to be on the identification and interpretation of cut and other butchery marks, and the differentiation between assemblages produced by human or carnivore agents. In comparison, there is something of a dearth of information on how butchery strategies might produce bias in element frequencies by selectively removing particular elements from the archaeological record. The literature on butchery marks is of little use here, since it describes processes such as skinning and filleting that do not necessarily lead to the destruction of the bones concerned. A more important process in this respect is that of grease and marrow extraction. Grease and marrow form a considerable part of the subsistence of a number of ethnographically described communities and its extraction involves the smashing and subsequent boiling of fresh bones (Binford 1978 pp152 - 163, Vehik 1977 pp170 - 171).

The probability of an element surviving an episode of marrow or grease processing is largely dependent on two sets of factors. Firstly, only certain bones are likely to be selected for this type of butchery. These bones are typically those which yield the greatest amount of the desired product. In practice, these tend to be the long bones. Gifford-Gonzalez (1989) has suggested, using ethnographic observation, that long bones are more thoroughly smashed than the less productive phalanges, tarsals and carpals, while vertebrae, “from which little additional nourishment can be gained by breaking them” (Gifford-Gonzalez 1989 p195), are even less affected by this type of processing. In addition to producing variability within the skeleton, this might result in variability between taxa, or indeed between animals of different ages from the same taxon, where the nutritional value of the skeleton varies between taxa or with age. Gifford-Gonzalez implies that these less valuable elements might be processed, but only at times of nutritional stress. A factor that governs the choice of which bones are processed for grease and marrow other than the food value of each element and the nutritional stress on the population concerned, has already been touched upon, while discussing the impact of carnivore gnawing on an assemblage. This could be loosely termed the “cultural factor”.

Cultural factors might vary between or even within communities, individuals or even seasonally. An example might be the reluctance of the Brazilian Mat’s to eat agouti (a medium sized mammal that is enthusiastically hunted by the surrounding tribes) (Milton 1997), or the Hindu abstinence from the consumption of cattle (Harris, 1965). Although it is often possible to construct complex and often convincing economically founded explanations of this behaviour (Simoons 1994), it cannot be modelled reliably. Yellen (1991a pp23 - 24) reminds us that there is no “template” to which ancient butchers worked. This cultural aspect of processing behaviour is reminiscent (although perhaps not analogous) to the behaviour of Stallibrass’s dog, Sappho, which inexplicably refused to eat the material fed to her in a gnawing experiment (see above) (Stallibrass 1990 pp158 - 161). However, in the selection of bones for butchery, cultural factors are likely to be ubiquitous, while Sappho’s unusual behaviour was very much the exception to a rule. Consequently, cultural factors will have a much more significant impact on element frequencies in an assemblage, than will the atypical behaviour occasionally observed in carnivores (or indeed humans).

Having determined, as closely as possible, the elements that are most likely to be selected for processing, the next important factor for consideration is the likelihood that each of these bones will survive the processing. Assuming that all of the bones are processed in a similar way, this is largely dependent on the physical strength of each element. This, in turn, is reliant on the density of the bone. Carter and Hayes (1976), Cheng *et al* (1998), Martin and Ishida (1989), and Turner-Walker and Parry (1995) have conclusively shown that bone density is the main provider of mechanical strength in bones. Consequently, denser bone will be the most likely to survive destructive butchery processes. Gifford-Gonzalez (1989 p195) points out that size is also a consideration here, because in her ethnographic study of the Dassanetch people of Kenya, certain elements (the pelvis and scapula) required a higher degree of breakage, so that they could fit into boiling pots of a limited size.

From this discussion it is apparent that the likelihood of any particular element (or element part) surviving the destructive effects of butchery is governed by a number of specific factors. These are the nutritional value of each skeletal part, the nutritional stresses on and the cultural preferences of the people concerned, and the density of each skeletal part being processed. These factors are potentially interconnected. For example, low density bones will contain relatively larger internal cavities. If these cavities contain marrow, then the nutritional value of the skeletal part will be increased.

3.3.5: Heating

Regardless of whether an animal has been butchered for its marrow, grease or meat content (or a combination of these), it is likely that the next stage of the preparation process will be cooking. Cooking can involve a variety of processes (eg baking, spit roasting or boiling), but always involves the application of heat. This heat has the potential to modify the bones chemically or physically in such a way that their ability to survive destructive taphonomic processes is altered. Consequently, cooking has the potential to produce bias in the archaeological record.

Since cooking and butchery are both part of the same food procurement process, the probability that a particular bone will be subjected to cooking depends on very similar factors as those discussed for butchery (above). The food value of a bone or animal part, the nutritional stress on the archaeological population at the time of the food processing, and cultural practice or personal whim are all significant in the decision making process that will lead to the inclusion or exclusion of a bone from the pot, oven, or spit. If bone is being burned as part of a refuse disposal regime, then other cultural factors (the definition and treatment of rubbish by the people concerned) will determine which bones will be burned.

The effect of heat on a bone is dependent on a number of other factors. Perhaps the most researched of these factors is the intensity and duration of the heating. In 1990 David published an account of a series of experiments that were designed to assess the characteristics of various natural and human-made types of fire. He also attempted to provide physical signatures on burned bones that would enable the colour and physical condition of burned bones to provide information about the temperature and duration of burning. He concluded that the higher the fire temperature, the greater the percentage of calcination of bones would be (p74). This conclusion was in general agreement with that of Gilchrist and Mytum (1986 p32), Nicholson (1993 p414) and Shipman (1988 p279). The fact that all such experiments have not provided precisely comparable results is symptomatic of the fact that colour is a poor indicator of the *exact* temperature to which a bone has been heated (Shipman *et al* 1984 p314).

Inextricably connected to fire temperature is the question of whether or not the bone was fleshed or defleshed at the time of firing. Binford (1972 p376) carried out burning experiments on a green monkey corpse and concluded that the presence of flesh provided an insulating covering to bones and so greatly reduced the effects of a fire (see also Gifford-Gonzalez 1989 p193). Implicit in this observation is that the cooking method (or alternatively, whether the bone was burned in order to extract food or as part of a waste disposal strategy) is an important consideration. All of the investigations cited above have attempted to link certain physical characteristics of a bone (in these cases, colour) with a specific set of burning conditions. This is intended to enable archaeologists to use the colour of the bone as a means of identifying the agent of burning. Other works have addressed additional physical characteristics, such as bone shrinkage (Coy 1975, Gilchrist and Mytum 1986, Shipman *et al* 1984), surface morphology (Nicholson 1993), microscopic morphology (Bradtmiller and Buikstra 1984, Holden *et al* 1995a , Holden *et al* 1995b, Nelson 1992) and crystal structure (Shipman *et al* 1984, Stiner *et al* 1995). There is, however, a lamentable paucity of literature that addresses the question of how burning might variously affect different bones, and ultimately produce biases in the archaeological record.

Chaplin is often quoted as having said that, "on none of the sites that I have examined where the bone is well preserved have I noted anything which suggests differential preservation due to possible cooking effects" (Chaplin 1971 p18). This view has been largely rejected since "in view of the lack of investigation of this topic one wonders how Chaplin knew which traces to look for" (Pearce and Luff 1994 p51). Although it is now generally agreed that burning has some effect on bone survival, it is still almost impossible to quantify, and so account for.

Some dog owners have suggested that dogs treat boiled and roasted bones differently, creating specific survival patterns, according to the cooking method (Kent

1981 p369, Pearce and Luff 1994 p51, Stallibrass 1990 p158). This information, however, is little more than anecdotal and it is still unclear whether the differential preservation is due to the carnivore's preference for bone that has been cooked in a certain way, or the bones ability to withstand carnivore action.

Data have been produced by Knight (1985) relating to the differential preservation of calcined and unburned bone in acidic environments. He demonstrated that calcined bone is considerably more prone to destruction by acidic environments than unburned bone. This is supported by the findings of Schiegl *et al* (1996 p780).

Knight (1985 p22) also investigated the crushing load of calcined bone. He concluded from these experiments that calcined bone is more fragile than unburned bone – a conclusion that is supported by Stiner *et al* (1995 p234). This is probably because heating bone causes the denaturation of its collagen, leading to an increase in its brittleness. Pearce and Luff (1994 p54) have added weight to this conclusion by demonstrating that boiled as well as burned bones have lower crushing loads than their untreated counterparts. They have also demonstrated that crushing loads decrease with higher roasting temperatures or longer boiling times. Knight (1985) also reported that the taxa and age at death remain relevant factors when assessing the impact of burning on bone survival. He also noted that the crushing load of a burned bone is correlated to its unburned density and that "a dense fresh bone is still a dense bone after incineration" (Knight 1985 p73).

An important point to consider at this stage is that, apart from in the case of very hot fires (Gilchrist and Mytum 1986), heating does not in itself lead to the analytical destruction of bone. It is subsequent forces (whether these occur during or after the heating event) that lead to the fragmentation of the bone. This implies that, providing that the heat treatment has a uniform effect on the material, the same variables as have already been discussed (density, size, nature of the destructive force, weathering stage etc.) largely govern the survival of bone material in the archaeological record. What is required is an investigation into how heat might *differentially* alter the mechanical properties of bone and lead to further biases in the archaeological record than have already been discussed.

This fleeting exploration into a very complex and well-researched topic has shown that the effects of heat on bone are multifaceted. First, it is necessary to consider the likelihood that a particular bone will be burned. This is dependent, to a large extent, on the food value of the skeletal part involved and any cultural influences that are active at the time. Next, the intensity of burning must be accounted for. Higher temperatures and a longer duration of heating will produce bone that is more prone to crushing. Quite how heating might differentially affect the mechanical properties of bone is unclear, but Knight's (1985) work suggests that, provided the material has all been treated in the same way, it will have the same *relative* properties as it did in an untreated state. This implies that strong unburned bones will remain relatively strong after heating. Naturally, this assumption needs to be confirmed through experimentation. Finally, following heating, certain bones might be more or less prone to destructive forces. For example, boiled bones might be more likely to be ravaged by dogs, while roasted bones, being largely dehydrated, will remain relatively inert in the soil and so will be less susceptible to chemical change during burial (Pearce and Luff 1994 p55).

3.4: The Primary Diagenetic Processes

In addition to the natural taphonomic and anthropogenic processes described above, a further set of processes that can create biases in the archaeological record come under the heading of "diagenesis". Diagenesis has been variously defined to include a wide range of chemical, physical and biological processes (see Lyman 1994 p506). Retallack (1990 p129) defines diagenesis as being "alteration after deposition ... taken to mean alteration after burial". For the purposes of this project, Retallack's definition will be used here. This project has defined diagenetic processes as being a subset of taphonomic processes. Schiffer (1995 p38) would define them as being n-transforms.

Diagenesis can involve chemical and physical change (caused by chemical, physical and biological agents) at a variety of structural levels. These changes may or may not result in preservation bias. Individual diagenetic processes are intimately linked to one another and are often interdependent. They are assumed to cease to operate if the bone is exhumed, (but will resume on reburial). A great deal of research into diagenesis has investigated processes such as trace element change (Balzer *et al* 1997 and references therein), crystal structure change (Weiner *et al* 1993) and amino acid racemization (Johnson and Miller 1997 and references therein), and how they might enable or adversely affect dating techniques or palaeodiet and palaeoenvironmental studies. Valid as they are, the majority of these studies do not address the potential of a particular diagenetic process to alter bone frequencies in archaeological deposits and so are of limited importance to this study. The processes that are directly relevant to this study are those that have clearly been demonstrated to affect bone preservation. They are the loss of bone collagen and the degradation of bone mineral and will be described in this section in turn.

A number of authors (discussed below) have carried out studies into how specific processes are mediated by setting up controlled laboratory experiments or by focussing on only one or two chemical or physical signatures which are known to be indicative of the process of interest. This approach provides information as to how individual diagenetic processes proceed and how they are mediated. Other researchers have observed general changes in bone condition or bone frequencies from assemblages that have been exposed to known or controlled conditions for a known or controlled time period. This type of report (referred to here as "actualistic" experiments) provides data as to how bone frequencies might be affected by diagenetic processes under certain conditions, even though the nature of these processes is not necessarily observed. Both types of approach are equally valid and will be discussed in turn. First, information regarding the specific processes of collagen loss and demineralisation will be described, and then a more general description of diagenesis, using data from actualistic studies will be provided. Finally, a means of identifying and quantifying the destructive effects of diagenesis will be described

3.4.1: Collagen loss

According to Oakley (1971 pp36 - 37), one of the first processes to affect bone following its burial is the loss of its organic matter. Collagen is the main organic component of fresh bone and forms a quarter of a bone's total weight. The removal of this water-insoluble protein has implications for the subsequent ability of a bone to survive mechanical forces as well as for the way in which other diagenetic processes will operate (see below). The removal of collagen from buried bone can be said to occur by three processes:

1) The removal of non-mineralised collagen by collagenase (see below), which has been produced by micro-organisms.
2) The removal of mineralised collagen (following demineralisation – see section 3.4.2) by collagenase, which has been produced by micro-organisms.
3) The removal of mineralised and non-mineralised collagen by non-enzymatic hydrolysis.

At the early stages of decomposition non-mineralised collagen (that which is not intimately associated with the mineral phase of the bone and so is accessible to micro-organisms) is broken down by collagenase. Collagenase is an enzyme mainly produced by species of *Clostridium*, especially *Clostridium histolyticum*. This micro-organism is absent in strongly acidic conditions (pH < 4 or 5). It flourishes in neutral conditions (pH = 7 or 8), but has been known to persist in slightly alkaline conditions (pH = 9) (Garlick 1971 p504). Thus, at this stage of decomposition, the rate at which non-mineralised collagen is broken down is closely linked to the presence of these micro-organisms and the suitability of the environment to support them. The temperature, pH and oxygenation of the matrix have therefore been suggested as being important mediating factors at this stage. Once the collagen has been denatured, it is removed from the bone matrix by leaching. Consequently, a through-flow of water also promotes this process (Garlick 1971 pp504 - 505). The removal of non-mineralised collagen by micro-organisms can, under laboratory conditions, take as little as a few days (Child and Pollard 1991 p618).

Collagen is rapidly decomposed by micro-organisms in most soil types, unless it is intimately associated with the mineral phase of the bone and so is inaccessible to micro-organisms. In this case a prerequisite (and so, mediating factor) of mineralised collagen degradation is the removal of bone mineral, through a variety of other processes, which liberates the protein and enables the micro-organisms to break it down (Child 1995 p168, Hackett 1981 p247, Millard 1998 p96). Millard (1998 p96) suggests that microbial attack of collagen that was mineralised in life is complete within 500 years (it should be noted, however, that this does not necessarily imply that all of the collagen would have been removed by this stage).

Alternatively, over the longer term, the collagen (including that which is inaccessible to the micro-organisms) will undergo a non-enzymatic hydrolysis reaction, resulting in its breaking down into smaller molecules and enabling it to be leached out of the bone matrix. Ortner *et al* (1972 p518) have suggested that this process can run to completion in 7500 years, given a mean annual soil temperature of 14.5 °C. The main factors that control the impact of hydrolysis are pH, soil temperature and soil hydrology. Water is needed, both to take part in the hydrolytic reaction with collagen (Collins *et al* 1995 p181) as well as to remove the reaction products through leaching (Von Endt and Ortner 1984 p248). Hare (1980 p212) has shown that the water naturally existing within bone is sufficient to enable non-enzymatic hydrolysis. The size and pore structure of the bone is of importance here, since it controls the external and internal surface areas (respectively) of the bone that can be in contact, and so react, with the groundwater (Hare 1980 p214, Hedges and Millard 1995 p157, Von Endt and Ortner 1984 p252). It also governs the rate at which water can pass through a buried bone and leach out the reaction products (Hedges and Millard 1995 p157). The importance of porosity in this process might explain the differences identified by Ortner *et al* (1972 p519) between rates of collagen loss from trabecular and cortical bone, since these two bone types have markedly different densities and density is necessarily linked to porosity.

Collagen-free bone is just as identifiable as fresh bone. Therefore, the removal of bone collagen does not in itself constitute analytical destruction and so no bias in the archaeological record will be produced. However, the removal of collagen is known to affect adversely the ability of a given bone to survive subsequent destructive processes (Turner-Walker and Parry 1995 p190, White and Hannus 1983 p316). Hare (1980) reminds us that even if hydrolysed collagen remains in the bone matrix in the form of soluble peptides and free amino acids (ie they have not been leached out) the bone's mechanical integrity is still impaired. Furthermore, removing collagen from a bone results in an increase in micro-porosity (and hence over all porosity) (Hedges *et al* 1995 p205). This effectively constitutes a decrease in the density of the bone. Consequently the bone is more susceptible to the taphonomic processes described in section 3.3.

Finally, the degradation of the mineral phase of a bone is partly dependent on the organic acids produced by micro-organisms as they attack the collagen. It is these acids that *initiate* the degradation of bone mineral, although it can proceed in their absence (White and Hannus 1983 pp321 - 322). In this way, the decomposition of collagen (and other soft tissues (Child 1995 p167)) indirectly results in bone demineralisation, which in turn leads to a loss of its mechanical integrity.

The laboratory based experiments mentioned above suggest that the loss of collagen from buried bone is governed by a number of factors. If collagenase-producing micro-organisms are involved, the suitability of the environment to support them (and therefore their proliferation in the soil) will have a significant effect on the rate of collagen loss. Otherwise, the level of through-flow of water, which removes the denatured collagen, will affect the rate at which collagen can be removed. The soil temperature will not only govern the proliferation of micro-organisms in the soil, but will also have a considerable impact on the rate at which the hydrolysis and other chemical reactions can occur. These processes do not in themselves cause biases in the archaeological record, but contribute to other processes that mediate bone destruction.

3.4.2: Mineral loss

While the organic degradation of buried bone operates on a short to medium time scale, the inorganic alteration of bone is a medium to long term process (Locock *et al* 1992 p297). According to White and Hannus, the chemical processes involved in calcium loss are intimately linked to the organic decomposition described above. Their four-stage model describes a sequence of reactions whereby:

> 1) Bone collagen is decomposed by micro-organisms when water and oxygen are present to form CO_2, HCO_3 ions and H ions, which in turn react with:
> 2) $Ca_5(PO_4)_3OH$ [bone hydroxyapatite] to form $(Ca_{5-x}H_{2x})(PO_4)_3(OH)$ and Ca ions, which can then react further either by:
> 3) CO_2, HCO_3 ions and H ions continuing to react with the hydrogen-enriched hydroxyapatite to decompose it to Ca and HPO_4 ions, or:
> 4) Ca ions from the soil solution replacing protons from the hydrogen-enriched hydroxyapatite to stop or retard the dissolution of the bone (White and Hannus 1983 pp321 - 322).

The implication of this series of reactions is that mineral decomposition of bone is triggered by the action of micro-organisms and so is to some extent reliant on the presence of the water and oxygen on which these micro-organisms depend. A through flow of groundwater will remove reaction products and promote the dissolution of the bone mineral (Hedges and Millard 1995 p159). Also implied in White and Hannus's (1983) model (point 4) is that in the presence of Calcium ions from the soil solution (ie in calcareous soils) demineralisation is inhibited or does not occur. In these respects soil conditions have a regulating effect on bone mineral loss. Since the temperature at which reactions take place has a significant effect on their rate, temperature is also a factor that partly governs demineralisation. When using the burial conditions to assess the likely impact of diagenetic alteration on an assemblage, it is important to consider the possibility of past environmental change. A change in the soil hydrology or chemistry (at any scale) will almost certainly produce changes in the diagenetic processes acting on the assemblage (Millard 1998 p99). Indeed, the presence of the bones themselves (or the micro-organisms that are decomposing them (Nicholson 1996 p524)) might be responsible for changes in soil chemistry.

If demineralisation is allowed to continue indefinitely, all of the bone mineral will eventually be removed and the bone will effectively disappear. However, even before this stage is reached, the mechanical resilience of the bone will be considerably weakened, leaving the bone prone to destruction by mechanical action.

The model proposed by White and Hannus (1983 p321 - 322) (above) highlights the role of soil chemistry and hydrology as well as the pH, temperature and ability for the matrix to support collagen-degrading micro-organisms in influencing the extent to which buried bone will be demineralised. Other factors that have been suggested to mediate the demineralisation of buried bone include the age of the animal at death (since the chemistry of the bone itself will change throughout an animal's lifetime) (Child 1995 p167). Also, the structure of an individual bone has some bearing on its susceptibility to demineralisation. Hedges and Millard (1995 p159) have highlighted pore structure as being of central importance when modelling bone mineral loss. Pore structure (ie "the distribution of porosity for a given pore radius" (Hedges and Millard 1995 p157)) governs the internal surface area which is available for solid – solution reactions. It also determines the rate at which groundwater can flow through the bone and the rate at which diffusion can take place. Pore-size structure also determines which pores will be filled with water and which will be empty (at any given level of soil moisture) and so controls which parts of bones will interact with soil water.

3.4.3: Histological destruction

The mechanisms for the decay of both the organic and mineral fractions of bone, described above, demonstrate that bone can degrade either through chemical (eg non-enzymatic hydrolysis) or biological processes (eg dissolution of mineral by organic acids produced by micro-organisms). The biological processes have been observed to result in distinctive patterns of histological destruction of buried bone. Although the exact pathways by which this destruction is achieved have not been conclusively proven, the subject warrants some discussion here.

This degradation of the histological integrity of buried bone has been variously described by Bell (1990 and references therein), Garland (1987) and Hackett (1981). It takes the form of various round foci or linear tunnels. These features may be the result of attack by bacteria and fungi of the genus *Mucor*, *Cladosporium* and *Candida* (and possibly others: see Turbanjust and Schramm 1998 p110). The invaders seem both to spread from the inner and outer cortical surfaces towards the centre of the bone, and to infiltrate the bone through the vascular channels and attack the osteonal bone from the osteonal canals. The organisms remove bone mineral by excreting organic acids (Sillen 1989 p220, White and Hannus 1983 p321 – see above) presumably in order to gain access to the collagen on which they depend (Hackett 1981 p247). As well as mineral loss, observations of mineral deposition (or redeposition) have been made (Hackett

1981 p247). Although histological destruction is treated as a diagenetic process here, it can potentially affect bone prior to its burial, provided that the micro-organisms required for histological destruction are present (Child and Pollard 1991 p619).

It is unfortunate that despite the work into this subject, we still have little understanding as to how it occurs or is controlled. Grupe *et al* (1993 p258) suggest that bones exhibiting tunnelling have little chance of becoming fossilised and that tunnelling will occur in the early stages of decomposition. What is certain is that histological destruction will not in itself lead to bone destruction. Rather, it will alter the porosity and mechanical properties of the bone, which will affect the impacts of subsequent destructive processes.

3.4.4: Actualistic diagenetic observations

The studies described so far have attempted to produce models that can explain or predict *specific* diagenetic processes. These models are often successful, at least in the controlled environment of the laboratory. However, actualistic studies of diagenetic processes acting on bone buried in less rigorously controlled field conditions have highlighted the complexities of bone alteration in the burial environment. Without an understanding of the interplay between the various post-burial processes that can act on bone it will be impossible to use data on the burial environment or the bone itself to predict alteration or loss of material. Below is a discussion of two factors – bone density and soil pH – which have been shown through actualistic diagenetic experiments to have non-linear or unpredictable relationships with diagenetic destruction.

Numerous laboratory and field based investigations have implicated bone porosity or density to be of some importance in predicting the progress of diagenesis (Hedges *et al* 1995 p205, Hedges and Millard 1995 p162, Henderson 1987 p44, Nicholson 1996 p529). Data provided by Lyman (1994 p261) indicate that 45.7% of the 184 assemblages that he studied were significantly and positively correlated with bone density. Of these, only 10.7% were ethnoarchaelogical. He therefore implies that the processes that act on archaeological bone material, but do not affect modern material, (ie post-depositional processes) are mediated to a greater extent by bone density. Nicholson (1996 p529) also identifies density as being an important variable here, but stresses that bone size is also of some importance and that "it is unclear at what point bone size becomes more important than bone density… in influencing bone loss". White and Hannus (1983 p318) failed to identify any significant correlation between bone decomposition (as measured by Ca:P ratios) and porosity. In this case, other, unidentified, factors must have been at work. Clearly the relationship between bone density and diagenetic loss exists, but is not a straightforward one.

A second factor that has often been assumed (and occasionally demonstrated) to affect bone decay rates is the pH of the soil (Garlick 1971 p504, Henderson 1987 p46, Millard 1998 p99). Essentially, bone is prone to destruction in low pH environments (below 4 or 5). This destruction involves the removal of the mineral component of the bone. However, in these conditions, the loss of collagen from the bone is inhibited. Although Gordon and Buikstra (1981 p569) found a relationship between soil pH and bone preservation, they concluded that the age at death of the animal was also of importance. Furthermore, their results implied that the ability for pH to predict bone loss was enhanced when age at death was not a variable. Further complications are apparent when it is considered that, although many of the species of fungi that are responsible for histological destruction can operate at a wide range of pH conditions, at near neutral pH their activities may be suppressed by competition with bacteria that themselves thrive in these conditions (Hanson and Buikstra 1987 p560). Furthermore, in conditions too acidic for soil microflora to operate, bone survival will not be enhanced since the acidic conditions will promote dissolution of bone mineral (Hanson and Buikstra 1987 p560).

Examples such as these should be sufficient to illustrate that, given the current level of knowledge, bone diagenesis remains essentially unpredictable. The complex interaction of the processes means that they can act in non-linear (and sometimes counter-intuitive) ways, and probably goes a long way towards explaining why researchers often fail even to identify a relationship between diagenetic alteration and duration of burial (Hedges *et al* 1995 p204, Locock *et al* 1992 p301). Furthermore, there is little information available regarding the effects of pre-burial treatment of material (such as cooking, skinning and weathering) on diagenesis, even though these have been identified as being important (Alcala and Escorza 1998 p103, Child 1995 p167, Henderson 1987 pp49 - 53, Nicholson 1996). Locock *et al* summed up the immensity of this problem when they wrote “it would appear that even a group of bones buried in a homogenous environment will be subject to decay at various speeds in an unpredictable way” (1992 p303).

It seems that, now that information from laboratory studies on how *individual* diagenetic processes proceed is available, field studies, such as that of Overton Down (Jewel 1963), are required to establish how these processes interact and how they affect bone survival. Given the long investment of time involved in such studies, it is unlikely that this information will immediately be forthcoming. For purely archaeological purposes, however, there are other approaches that do not necessarily attempt to explain in detail the factors affecting bone degradation and loss as a result of diagenesis. These approaches aim to provide models against which loss can be assessed and will be discussed below.

3.4.5: Identifying and accounting for diagenesis

It is apparent that the complexities of assessing the impact of diagenesis on bone frequencies (by referring to the data available from the burial matrix and bones themselves) are prohibitive. It is also inappropriate to use the macroscopic appearance of the material itself, since it has long been established that macroscopic appearance and diagenetic alteration are not necessarily related (Hanson and Buikstra 1987 p553, Hedges *et al* 1995 p207, Locock *et al* 1992 p301, Oakley 1971 p37). Furthermore, the spatial variability with which diagenesis can affect bone is so great that the number of observations that would be required to provide a reliable indication of the impact that diagenesis has had on an assemblage is enormous (Hedges *et al* 1995 p202). Finally, even if it could be identified, there is little consensus as to how to *measure* bone decay (Locock *et al* 1992 p297).

An alternative approach has been proposed by Klein and Cruz-Uribe (1984 pp69 - 76). Rather than examining features of the bones themselves, these authors focussed on the assemblage as a whole. They used data relating to bone density to predict the bone frequencies likely to be found in a diagenetically altered assemblage. Their conclusion was that “any archaeological assemblage that is comparably rich in small, hard, compact bones has probably suffered greatly from post-depositional destruction” (Klein and Cruz-Uribe 1984 p71). This approach relies on the assumption that density is the overriding factor that governs diagenetic destruction. This assumption has not been conclusively demonstrated experimentally, but is a “reasonable hypothesis” (Marean 1991 p678) and has successfully been used to explain post-depositional destruction by Grayson (1989 pp647 - 650), Klein (1989 p378) and Klein and Cruz-Uribe (1984 pp69 - 74).

This approach does not necessarily identify which particular processes are responsible for forming the assemblage and will be of little use to researchers who are investigating particular chemical or physical changes within the bone. However, in this project, where bone frequencies are of prime interest, it is a valuable tool for identifying the extent to which diagenetic processes have altered an assemblage.

The method proposed by Klein and Cruz-Uribe (1984) was built upon by Klein (1989) who emphasised the importance of bone size in assessing the impact of diagenetic processes on an assemblage. He suggested that smaller elements were less likely to be affected adversely by pre-depositional processes such as butchery and trampling and so their presence or absence from the archaeological record will be the result of diagenetic processes alone (Klein 1989 p374-375).

A further refinement of Klein and Cruz-Uribe's approach was offered by Marean (1991). Marean stated that the elements used to assess post-depositional alteration of assemblages should be independent of the pre-depositional transport and food preparation activities of people, as well as being "independent of the calculation procedure for archaeozoological measures of element abundance" (Marean 1991 p680). Following a series of experiments and observations, Marean determined that the most suitable elements for assessing post-depositional destruction are carpals and tarsals (excluding calcanea) that show no evidence of gnawing, digestion, weathering, butchery or percussion. He also noted that bones of a single species (or multiple similarly sized species) should be used. These criteria mean that any differences in bone frequencies between sites or contexts will be the result of post-depositional processes, rather than pre-depositional treatment, or the size or density of the bones themselves. Carpals and tarsals were used, because Marean determined that these are the elements least likely to be affected by pre-burial fragmentation. Consequently, when these elements are broken, post-burial (diagenetic) processes are implicated.

Marean employed a statistic called the "completeness index" to assess the degree of fragmentation of archaeological material. The completeness index is derived by "estimating for each specimen the fraction of the original compact bone that is present, summing the values and dividing that by the total number of specimens ascribed to that bone and taxon" (Marean 1991 p685). By multiplying the result of this calculation by 100, a mean percent completeness was obtained. Figure 3.2 shows this.

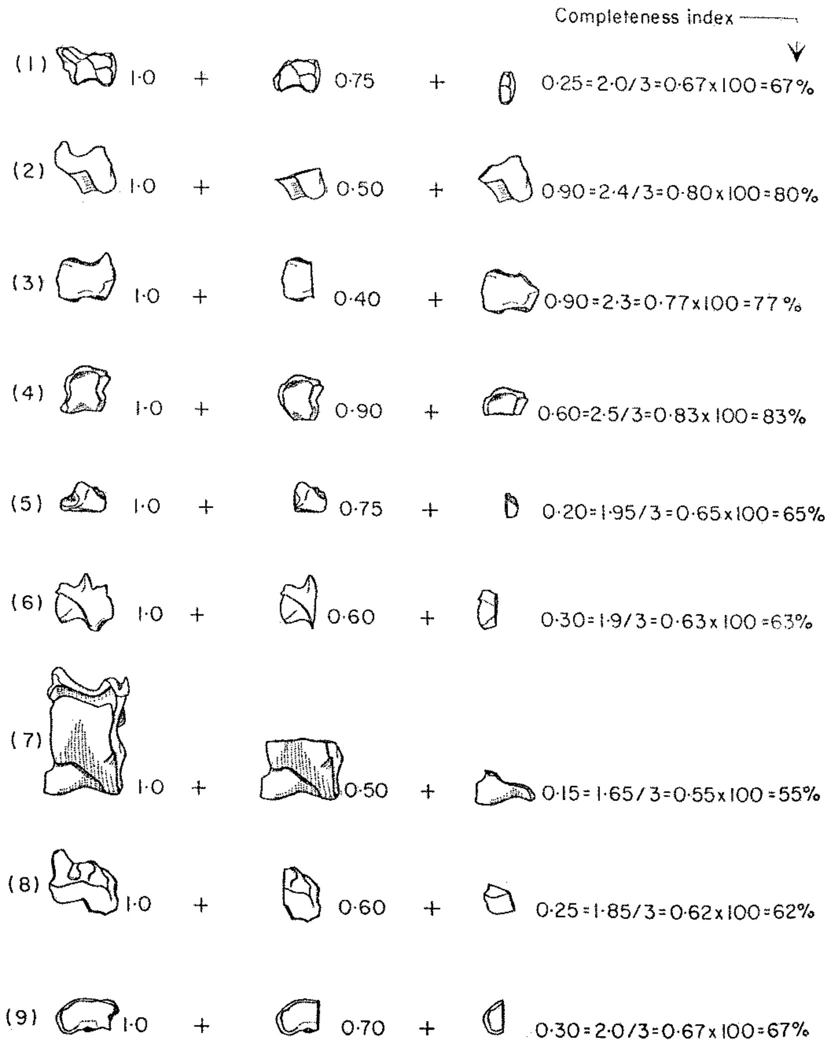

Figure 3.2: Examples of the calculation procedure for the completeness index. The bones illustrated are all from bovids and include the (1) lunate, (2) cuneiform, (3) scaphoid, (4) magnum, (5) unciform, (6) fibula, (7) astragalus, (8) navicular cuboid and (9) external cuneiform. From Marean (1991 p686 Fig 1).

By comparing the completeness index of material from different sites or contexts, it is possible to assess the extent to which diagenetic destruction has affected the faunal material. Marean (1991 p690) reminds us that comparisons between assemblages that exhibit different degrees of diagenetic destruction will be imperfect. Also, comparisons of the completeness index enable assemblages to be *ranked* in terms of diagenetic alteration. This will allow an assessment of the differences in bone frequencies between assemblages that differ only in their degree of diagenetic alteration.

Once again, this approach to assessing diagenesis offers little information regarding the nature of the processes at work, but concentrates on its gross effects.

A final investigation that has examined the problems of recognising the effects of diagenesis is that of Alcala and Escorza (1998). These authors examined the possibility of characterising the morphology of bone breaks that is particular to diagenetically altered bone. They concluded that diagenetically altered bone would tend to exhibit clear, simple planes that are perpendicular to the longitudinal axis of the bone. Also, such bones would tend to be broken at specific bone locations (the mid-shaft point or the ends of the diaphysis in the case of the study sample – prehistoric horse metapodia) (Alcala and Escorza 1998 p106). Finally, fragments of bones broken post-depositionally will tend to be recovered in close proximity to each other (Alcala and Escorza 1998 p103). This study shows some promise as a tool for recognising diagenetic destruction, but not until further work on a wider range of elements and taxa has been completed and only on sites which employ a very highly refined recording protocol.

3.5: Summary

It is now clear that a large number of variables are responsible for controlling the destructive effects of taphonomic processes. However, bone density plays an important role in each case (Stiner *et al* 2001 p644). This is especially true of natural taphonomic processes. Often, the likelihood that a bone will be subjected to a destructive process can be said to be largely the result of human decision making, although it is primarily bone density that governs whether the bone will survive this process. The factors that control the progress of diagenesis are complex and, at present, poorly understood. However, diagenesis itself does not lead to analytic destruction of bone. It simply alters the ability for a bone to withstand subsequent destructive forces. To this end, bone density is connected to bone destruction associated with diagenesis. Although the complexity of diagenetic processes means that they cannot be reliably modelled, procedures are available that enable the impact of diagenesis on a bone assemblage to be assessed.

Schiffer (1995) has noted that “laws” need to be established by which transformation processes might be understood. The “laws” to be used by this project relate to bone density. They predict that very dense bones will survive destructive processes more frequently than much less dense bones.

It is apparent that bone density data will prove to be a useful tool when accounting for preservation bias in the archaeological record. This is especially true if density data are combined with data relating to "taphonomic signatures" (the physical evidence of weathering, gnawing and other processes on the bones themselves). However, this chapter has also highlighted the fact that numerous other factors exist that are also capable of affecting the impact of destructive forces. One of the objectives of this project is to assess the extent to which bone density alone can be used to overcome bias in element frequencies.

This chapter has presented a wide range of destructive processes that are known to result in bias in the archaeological record. It is clear that one of the prime factors mediating these processes is bone density. It can therefore be argued that bone density data is a potentially useful tool in researching the biases in zooarchaeological assemblages.