Chapter 6

Bone Fracture and Within-bone Nutrients: an Experimentally Based Method for Investigating Levels of Marrow Extraction

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Animal fat plays a very important role in the diet of most hunter-gatherer peoples and primitive pastoralists or farmers, whether past or present. Fats have a much higher calorific value than either protein or carbohydrates, by a ratio of 9:4 (Erasmus 1986; Mead *et al.* 1986). As such, in any community where there is dietary stress, the heavy exploitation of fat resources may be the only means of survival. This will particularly be the case where a given people are very dependent upon animal products and have little access to sources of carbohydrate. The Inuit would be a good example of such a group. The exclusive consumption of lean meat can lead to severe dietary problems (Speth 1987). One of the most obvious and reliable of sources of fat is the bones. Even when an animal is, itself, suffering from dietary stress and is very lean, there will still be plenty of fat within its medullary cavities. The marrow is the last resource of fat to be exhausted in the fat-mobilization sequence of a starving animal (Peterson *et al.* 1982; Brookes *et al.* 1977; Davis *et al.* 1987).

Faunal analysts have, for a very long time, noted the breaking of bones for the extraction of marrow. Their criterion has always been the presence of a fresh fracture type. These 'helical' fractures, produced when a fresh bone is dynamically fractured, are usually taken as being indicative of the deliberate breaking of bones and this is, quite reasonably, associated with marrow extraction. Such a methodology, for identifying individual instances of marrow extraction, is all well and good. However, if one wishes to assess levels of within-bone fat exploitation throughout whole assemblages, matters become somewhat more complex.

Medullary cavities are not the only sources of bone fat. In many ethnographic examples, grease is extracted by boiling comminuted cancellous bone from appendicular epiphyses and axial elements. The fat is then skimmed from the surface of the water once it has been cooled by the addition of cold water or snow (Binford 1978; Leechman 1951; 1954; Davis & Fisher 1990). This will lead to a great deal of fragmentation in the assemblage. Post-depositional taphonomic agents will then take their toll, increasing fragmentation still further and confusing the fracture patterns. In order to assess levels of bone fat exploitation in an assemblage, many variables must be considered. Levels of fragmentation must be assessed for different types of bone (i.e. diaphysis, epiphysis, axial etc.). Levels of dog gnawing, burning, modern damage and other forms of attrition must be considered. Most importantly, there must be a method for indexing the extent to which diaphysis fragments bear the signs of having been fractured 'fresh'. Examining a shaft cylinder for fresh fracture type poses few problems but where fragmentation is heavy, and only shaft splinters remain, things become more difficult. What is required is a fracture freshness index based upon criteria that do not require a whole bone circumference, and that can be calculated quickly, for a large number of specimens. The establishment of such an indexing method for fracture freshness is the subject of this paper.

This matter is, however, further complicated by the fact that, in many ethnographic examples, bones are not entirely fresh when they are fractured for marrow. There are instances of bones being frozen, being warmed near a fire or heated in water by Nunamiut Eskimo (Binford 1978), to take just one ethnographic example. The reason for heating bones prior to fracture is rarely given in ethnographic accounts. The Kutse bushmen of the Kalahari warm bones (but do not char them) before fracture and then suck out the marrow (Kent 1993, 338). In this instance, it is likely that the warming is intended to melt the outside of the marrow, hence making it possible to suck it out. The !Kung San warm bones by boiling them. This, apparently, gives the marrow a 'desirable consistency' whilst roasting makes it 'too thin' (Yellen 1991, 13).

Johnson (1985) describes the nature of fresh fractures in detail and also indicates that fresh fracture type is easily affected by anything that alters water content or creates micro-cracks. It is, therefore, of paramount importance to establish whether ethnographic examples of pre-marrow extraction bone treatments affect fracture type, thereby inhibiting the identification of marrow extraction. Below, a series of fracture experiments, which emulate ethnographic examples, are described. A method of indexing freshness of fracture is outlined and then tested against the laboratory generated fracture specimens to see whether, firstly, the index is sensitive to changes in fracture type and, secondly, whether pre-marrow extraction treatments of bone will so affect fracture freshness as to make it difficult to separate those bones from ones fractured, after loss of freshness, through some other taphonomic mechanism.

Experimental methods

All the bones in the experiments outlined below were fractured using the same method. Before fracturing took place the bones were cleaned of meat, connective tissues and as much of the periosteum as possible. They were laid upon a stone anvil and struck, mid-diaphysis, with a sharp blow with a water-rounded flint pebble. Further blows to the same spot were used, if necessary, to fracture the entire circumference of the bone, so that it could be parted in two.

After fracturing, the marrow was extracted using a variety of long, metal implements. As many as possible of the fragments resulting from the fracture were collected. For the purposes of preservation, the two halves of the bone and all accompanying fragments were boiled for two hours in a fine net bag and then any remaining soft tissue was removed. The specimens were then degreased by immersion for a short period of time in boiling sodium hydroxide solution, rinsed and allowed to dry.

All the bones used were cattle bones collected in a fresh state (no more than a day old). Many specimens were from fairly young animals with epiphyses not fully fused but with diaphyses of adult size. The exact number of bones and the elements used for specific experiments were largely governed by the fresh supply available at the time of the experiment. The experiments are outlined below.

Fresh specimens
The sample of fresh bones (no more than a day old) consisted of seven specimens; two humeri, one radius, one metacarpus, one femur and two tibia.

Frozen specimens
Four experiments were carried out on frozen bones. Six bones (one humerus, one radius, one metacarpus, one femur, one tibia, one metatarsus) were frozen for two weeks at –20°C and then thawed before fracture. The freezer temperature was maintained by the regular checking of a thermometer. Four bones (one humerus, one radius, one femur, one tibia) were frozen at the same temperature for four weeks and then defrosted. Six specimens (one humerus, one radius, one metacarpus, one femur, one tibia, one metatarsus) were treated to a much longer period of freezing, 20 weeks, before thawing. The fourth experiment was carried out on only two bones (one humerus, one radius) which were frozen at –20°C for 10 weeks but fractured in their frozen state.

Oven-heated specimens
Three experiments were conducted where the specimens were heated in an incubation oven. Four bones (one humerus, one radius, one femur, one tibia) were heated for one hour at between 80 and 100°C. The bones were then fractured fresh from the oven and the maximum temperature of the marrow measured with the use of a digital thermometer. The second experiment followed the same procedures but the four specimens (one humerus, one radius, one femur, one tibia) were heated for five hours. The third experiment, intended to provoke more extreme results, involved heating three bones (one humerus, one radius, one tibia) to between 100 and 120°C for a total of 43 hours. These specimens were also fractured fresh from the oven. The oven temperatures are quoted as ranges because of the oven's slowness in regaining its intended temperature after insertion of the specimens. The temperature of the oven was monitored by the use of a probe attached to a digital thermometer outside the oven.

Boiled specimens
Two boiling experiments were conducted. The first involved boiling three bones (one tibia, two radii) for 10 minutes before fracturing them immediately after withdrawal from the water. The maximum temperature of the marrow was recorded after fracture.

Four bones (one humerus, one radius, one femur, one tibia) were boiled for one hour and treated as above.

Specimens subjected to radiant heat

This experiment was designed to replicate the heating of bones placed immediately adjacent to a wood fire. This was achieved by recording the temperature reached by a mercury oven thermometer, placed approximately 15 cm from a domestic-sized wood fire, and reproducing the same effect, in the laboratory, with the use of an electric bar fire positioned to make the thermometer read the same temperature. Obviously the temperature of fires will vary tremendously and different distances from the fire would also cause considerable variation. The purpose of these measurements, however, was simply to produce conditions which are in the correct general range of magnitude. The temperature reached by the thermometer was in the range between 200 and 250°C. This, however, cannot be taken to represent the temperature reached by bones in the experiments below, since the thermometer and the bone will differ in their specific heat capacity and radiative and reflective properties. These figures must be taken as representing nothing more than an indication of the general order of magnitude in the heating.

Figure 6.1. *The right-hand fracture on this femur shaft is an archetypal spiral fracture, exhibiting a helical outline and a smooth fracture surface which is at an obtuse or acute angle to the cortical surface.*

The first experiment conducted with radiant heat was carried out on three specimens (one tibia, two radii). These specimens were subjected to the above specified radiant heat for six minutes on one side of the bone only. The bones were fractured (by striking heated side) immediately after heating and the maximum temperature of the marrow was recorded after fracture. The second experiment involved subjecting four bones (two tibiæ, two radii) to radiant heat for four minutes. In this case the heat was applied evenly round the bone shafts (the bones were slowly rotated). Fracture took place immediately after heating and the marrow temperature was once again taken.

Radiantly-heated frozen specimens

Four specimens (one humerus, one radius, one femur, one tibia) were frozen for ten weeks at –20°C and, whilst still frozen, were subjected to radiant heat (as above) for ten minutes on one side. The bones were fractured immediately after heating and the temperature of the marrow taken on both the heated and unheated sides of the shaft.

Analytical methods

Each fracture created in the above experiments was analyzed for a series of criteria. These criteria largely follow those outlined by Morlan (1984), Johnson (1985) and Villa & Mahieu (1991), and they are described below. After subjective analysis according to these criteria, the fractures were all assigned 'fracture freshness index' (FFI) values according to the method outlined below.

Fracture outline

The fracture outline is a description of the fracture's basic shape. Fresh bones are generally expected to fracture with a helical fracture. This is a curved fracture that spirals its way round the diaphysis (see Figs. 6.1 & 6.2a). Other outlines tend to be straight breaks, whether they are diagonal, transverse or longitudinal (Fig. 6.2b, c & d). It is important not to confuse a helical outline (Fig. 6.2a) with a diagonal fracture (Fig. 6.2d). A combination of outline types may co-exist in a single fracture. In this analysis the outline types to be found on both the proximal and distal ends of the fractured specimen are described. If no separate fragments were broken away, the two ends will have the mirror image of each other's fractures, but when large fragments are dislodged their outline can be very different.

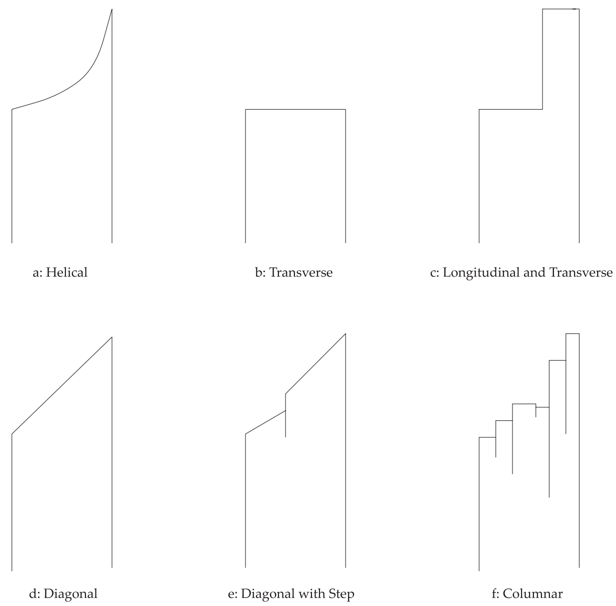

Figure 6.2. *A figure showing the shape of some possible bone fracture outlines: a) helical; b) transverse; c) longitudinal and transverse; d) diagonal; e) diagonal with a step; f) columnar.*

Fracture edge texture

The broken surface of a fresh fracture is usually smooth in nature, whilst on less fresh specimens it may be of rough appearance. In carrying out this aspect of the analysis, it is important to disregard roughness or jaggedness on small areas caused by stress relief features (as described by Johnson 1985), where the fracture line has rippled. Roughness resulting from lack of freshness is relatively easily discerned. The fracture surface appears granular, rather like the edge of a sherd of coarse earthenware or a broken biscuit (see Fig. 6.3). The edge of fresh fractured bone, however, looks more like broken plastic (see Fig. 6.4).

Fracture angle

On a fresh fracture, the angle of the fracture surface to the bone's cortical surface is usually acute or obtuse. Right angles are more common on unfresh specimens. Figure 6.5 illustrates acute, obtuse and right-angle fractures. For this study, an estimate of the approximate percentage of fracture surface that was at right angles was made for both the proximal and distal ends of the bone.

Steps and columns

On unfresh specimens, the fracture outline can become interrupted by micro-cracks already present in the bone. These micro-cracks, which are usually caused by loss of water content in the bone (Johnson 1985), tend to be followed by a fracture line, for a distance, creating a step in the fracture outline (see Fig. 6.2e). When this effect becomes very serious the fracture outline may largely consist of small stepped columns (see Figs. 6.2f & 6.6). The presence or absence of such features was noted.

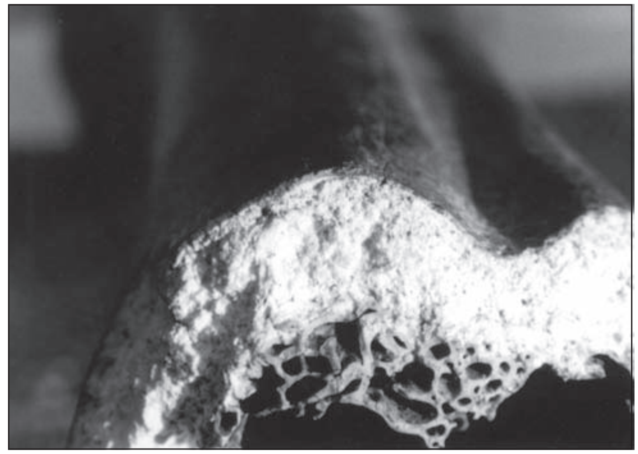

Figure 6.3. *A very granular and rough fracture surface on a metapodial, broken after most of its organic content had been lost.*

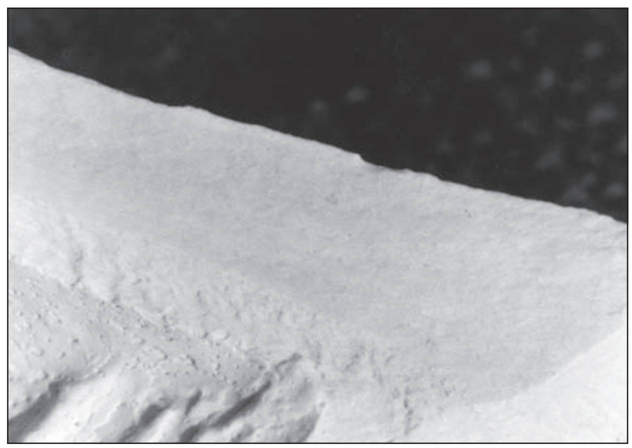

Figure 6.4. *The very smooth fracture surface on a humerus broken whilst fresh.*

Other features

On fresh fractures, an impact point is often clearly distinguishable and the fracture fronts run out radially from this point (Fig. 6.7). An impact scar is left at the point of impact and, if the bone was struck whilst on a hard surface such as an anvil, there will also be a rebound scar on the other side of the shaft, as a result of equal and opposite forces (Fig. 6.8). Fresh fractures tend to terminate before the articulation

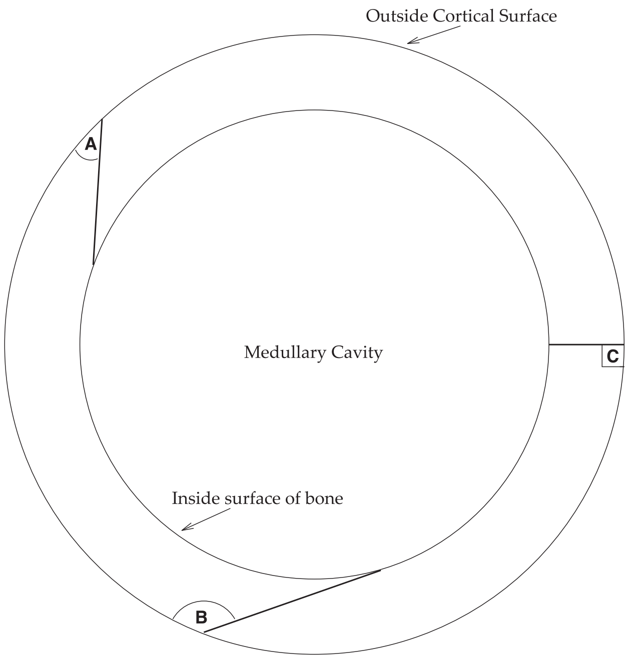

Figure 6.5. *A figure looking longways down the medullary cavity of a longbone showing three possible angles of fracture to the bone's cortical surface: A) acute; B) obtuse; C) at right angles.*

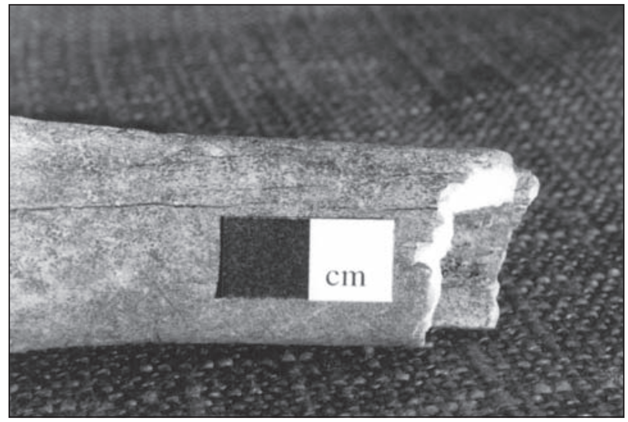

Figure 6.6. *The fracture on this bone exhibits a columnar fracture outline which is symptomatic of the bone having been fractured in an unfresh state after many micro-cracks had formed.*

Figure 6.7. *Spiral fracture lines radiate out from a central impact point on this fresh-fractured humerus.*

Figure 6.8. *This archaeological example of a fresh-fractured shaft splinter exhibits both impact and rebound scars. This suggests that the bone was fractured on an anvil.*

but, on unfresh bones, the fracture might continue and cut across the articulation (Johnson 1985). Information regarding these points was noted.

The Fracture Freshness Index (FFI)

The three principal criteria of fracture angle (criterion A), outline (B) and edge texture (C) were used in the creation of the fracture freshness index. These criteria are being used because they can be applied to all fragments (i.e. impact points, steps etc. cannot be expected to be present on all fragments) irrelevant of whether the whole diaphysis circumference survives or not. For each criterion, a score of zero, one or two was given to each fragment. Zero was scored if the fragment was entirely consistent with fresh fracture according to that criterion. One was scored if some 'unfresh' features were present and two was scored if 'unfresh' features dominated.

Therefore, if a fragment had no fracture surface at 90° to the cortical surface it would score zero for that criterion. If, for instance, 40 per cent of the fracture were at 90° then it would score one. If 50 per cent or more were at 90° then it would score two. For fracture outline, the presence of only a helical fracture means a score of zero, a mixture of fracture type means a score of one and a complete absence of

Table 6.1. *Summary of fracture experiment results.*

Experiment **Element**	**% at 90°**	**Outline**	**Texture**
Fresh			
Humerus	15	H	S
Radius	0	H	S
M'carpal	5	HL	S
Femur	0	H	S
Tibia	0	H	S
Humerus	0	H	S
Tibia	0	H	S
2 wk Frozen			
Humerus	40	H	SR
Radius	30	H	SR
M'carpal	5	HL	S
Femur	0	H	S
Tibia	0	H	S
M'tarsal	20	HL	S
4 wk Frozen			
Humerus	0	H	S
Radius	10	H	SR
Femur	0	H	S
Tibia	20	H	S
20 wk Frozen			
Humerus	10	H	S
Radius	20	H	S
M'carpal	25	H	SR
Femur	15	HD	SR
Tibia	35	HL	SR
M'tarsal	0	HL	S
10 wk Frozen (not thawed)			
Humerus	10	H	S
Radius	10	H	S
1 hr in Oven			
Humerus	30	H	SR
Radius	15	TLD	SR
Femur	5	HL	SR
Tibia	20	H	S
5 hr in Oven			
Humerus	35	TH	RS
Radius	0	LD	R
Femur	15	DLH	SR
Tibia	30	DL	SR
43 hr in Oven			
Humerus	45	TLD	R
Radius	50	TLD	R
Tibia	0	TLD	RS
10 min. Boiled			
Tibia	10	HL	SR
Radius	50	HT	SR
Radius	0	H	SR
1 hr Boiled			
Humerus	50	TLD	R
Radius	†	LD	R
Femur	0	HD	SR
Tibia	60	HL	R
Radiant Heat: 6 min., 1 side			
Tibia	0	H	SR
Radius	10	HD	SR
Radius	7.5	LDTH	RS
Radiant Heat: 4 min., even			
Tibia	0	H	S
Tibia	20	HT	SR
Radius	10	H	S
Radius	30	HLD	SR
Frozen 10 wk, Radiant Heat 10 min., 1 side			
Humerus	0	H	SR
Radius	70	TLD	R
Femur	27.5	HT	SR
Tibia	17.5	HL	SR

Key:
H = Helical, L = Longitudinal, T = Transverse, D = Diagonal.
Combinations of letters mean more than one outline type is present.
R = Rough, S = Smooth, SR = more smooth than rough, RS = more rough than smooth.
† = This specimen was far too jagged to be assessed for angle criterion.

helical fracture means a score of two. For fracture texture, zero means an absence of roughness (apart from aforementioned stress-relief features), one means some roughness but mainly smooth and two means largely rough.

To create the index value for a given fragment, the scores for the three criteria are summed up. This gives an index ranging from zero to six. Zero indicates a specimen entirely consistent with fresh fracture and six indicates a specimen that has lost almost all fresh fracture features. To create an average index value for each of the experiments, the mean of scores for each criterion was calculated for all specimens in that experiment and then those means were summed.

It is important to note that this scoring system is deliberately rough and ready. It is based on criteria that can be assessed very quickly by estimation. Fracture angles are not measured, nor should they be. Whether or not rough fracture surface dominates is estimated, detailed percentages are not arrived at through measurement. Some authors, for example Biddick & Tommenchuck (1975), have attempted detailed recording systems for fracture outline, but such methods are very time-consuming (and descriptive

Table 6.2. *Mean criteria scores and fracture freshness index by experiment.*

Experiment	A	B	C	Index
Fresh	0.29	0.14	0.00	0.43
2 Weeks Frozen	0.67	0.33	0.33	1.33
4 Weeks Frozen	0.50	0.00	0.25	0.75
20 Weeks Frozen	1.00	0.50	0.50	2.00
10 Weeks Frozen (not thawed)	1.00	0.00	0.00	1.00
1 Hour in Oven	1.00	0.75	0.75	2.50
5 Hours in Oven	0.75	1.50	1.50	3.75
43 Hours in Oven	1.00	2.00	2.00	5.00
10 Minutes Boiled	1.00	0.67	1.00	2.67
1 Hour Boiled	1.33	1.50	1.75	4.58
Radiant Heat (6 min., 1 side)	0.67	0.67	1.33	2.67
Radiant Heat (4 min., even)	0.75	0.75	0.75	2.25
10 wks Frozen, 10 min. Radiant Heat	1.00	1.00	1.25	3.25

rather than interpretative) and unlikely to be applicable to the analysis of large assemblages. In using a quick scoring system, like the one suggested here, there is likely to be some error on individual specimens. The aim of this study is not to interpret individual specimens, however, but large assemblages, where errors are likely to average out.

Results and observations

Table 6.1 gives a summary of the results obtained from each experiment. The original recording was in far greater detail. Table 6.2 gives the mean scores for each experiment and the FFI value (angle is A, outline is B and texture is C). Below, observations on each of the experiments are made.

Fresh

All the fresh specimens fractured according to expectations. The outlines of the fractures were helical and the edges were smooth. The metacarpus, however, had a slight area of longitudinal fracture, but this was almost certainly a result of the natural division down the centre of the metapodials of artiodactyls. The fracture angle was rarely at right angles. Most of the specimens displayed clear impact points and some also showed rebound points. The point of rebound is like a second impact point, on the underside of the bone, where the bone rebounded off the anvil (Johnson 1985). The fracture of fresh bones required, on the whole, just a single sharp blow. The average FFI value was 0.43.

Two weeks frozen (thawed)

Once again, the fractures were largely smooth and helical with some longitudinal fracturing on the metapodials. Both the humerus and radius, however, had a certain amount of right angle fracturing. Impact points were often present. The ease of fracture was the same as for fresh specimens. The average FFI value was 1.33.

Four weeks frozen (thawed)

Fractures were again helical and largely smooth with very little fracture at right angles. Impact points were present in all but one specimen. One blow was normally required for fracture. The average FFI value was 0.75.

Twenty weeks frozen (thawed)

Fracture was still largely helical after twenty weeks frozen. However, there was some diagonal fracture on a femur, some longitudinal fracture on a tibia and the expected longitudinal fracture on metapodials. The outlines were slightly more jagged and less uniform than those found on experiments described above. The fracture surfaces were generally smooth. Some right-angle fracture was encountered on every specimen, although in small amounts. Impact points were generally still present and fracture was still achievable with a single sharp blow. The average FFI value was 2.00.

Ten weeks frozen (not thawed)

The two specimens broken whilst frozen created smooth, helical fractures with very small amounts of right angle fracture. Impact points were present and fracture was easily carried out. The average FFI value was 1.00.

One hour in oven

Fracture of these specimens produced largely helical fractures. The femur produced some longitudinal fractures but the radius was the major exception creating a combination of diagonal, longitudinal and transverse fractures, with very little helical fracture present. Some roughness on edges was encountered on three of the four specimens. Some right angle fracture was present on all specimens. Impact points, as such, were generally absent. Instead, an area of crushing was often present. Some of the specimens were distinctly harder to break than fresh or frozen specimens. After breaking it was observed that the marrow in the cavities was loose, because a fair portion of it was molten. The temperature of the molten marrow was *c.* 45°C at the time of breaking. The average FFI value was 2.50.

Five hours in oven

Some helical fractures were present, but most fractures consisted of a mix of outline types. The radius was particularly jagged. There was a degree of roughness on all fracture surfaces. Right-angle fracture was present in significant quantities on the humerus and tibia and also present on the femur. The radius was free from any right angles owing to its jaggedness. No impact points were present. These specimens were not difficult to break. Much of the marrow fat was liquid in the cavity. This fat was *c.* 75°C at the time of breaking. The average FFI value was 3.75.

Forty-three hours in oven
No helical fracture was present. Instead there was a combination of other outline types. The edges were rough or largely rough. No impact points were present and the articulations were crosscut on both the humerus and radius. Two of the three specimens had large proportions of right-angle fracture. Upon impact the specimens shattered creating many small fragments. The marrow cavities were completely dried out. The average FFI value was 5.00.

Boiled for ten minutes
The fractures on these specimens were largely helical and smooth. One radius, however, had some rough, transverse fracture. This specimen also had a large degree of right-angle fracture. The other two specimens had little or no right-angle fracture. Impact points were not present and the bones were more difficult to break than fresh ones. Upon fracture the marrow was partly molten and at a temperature ranging between 57°C and 67°C for the different specimens. The average FFI value was 2.67.

Boiled for one hour
On the humerus and radius, helical fracture was entirely absent and on the tibia there was a mixture of helical and longitudinal fracture. The femur was anomalous in having mainly smooth, helical fracture without right angles. The humerus and tibia featured much rough, right-angle fracture. Because the radius was jagged and saw-tooth in its fracture outline it was impossible to assess proportions of right-angle fracture. These bones were incredibly difficult to break and upon fracture the marrow cavities were almost entirely devoid of marrow. The marrow had presumably all melted and made its way out of the bone through the foramen. The average FFI value was 4.58.

Six minutes radiant heat, one side
This experiment resulted in a degree of helical fracture on all specimens, mixed with other fracture types. Similarly there was a mixture of rough and smooth fracture on each specimen. Right-angle fractures were present in only small quantities. An impact point was present on one specimen. The heated side of the bone had not been browned or charred in any way as a result of its treatment. The marrow was, however, quite hot and molten on the heated side. The maximum marrow temperature ranged be-tween 60°C and 74°C on the different specimens. The specimens were slightly harder to break than fresh bones. The average FFI value was 2.67.

Four minutes radiant heat, even
Most of the fractures were largely helical and smooth. Right-angle fractures were present on three of the four specimens, but in fairly low proportions. Impact points were present on two examples and one rebound point was present. The bones were not particularly difficult to break and the marrow was part molten round the edges with maximum temperatures ranging from 31°C to 52°C. The average FFI value was 2.25.

Ten weeks frozen, ten minutes radiant heat, one side
The humerus was the only specimen to produce a largely helical, smooth fracture. The femur and tibia produced a combination of helical and other fracture types and had both rough and smooth fracture surfaces. The radius produced mainly rough fractures with transverse, longitudinal and diagonal outlines. The radius also produced this series of experiments' only clear steps caused by cracks present prior to fracture. Two large, right-angled steps were present on the heated side of the bone. Two cracks, probably resulting from differential expansion caused by sudden heating of the frozen bone (heat shock), had clearly interrupted the fracture path. All but the humerus had proportions of right-angle fracture. The radius had very high proportions. An impact point was only present on the humerus. The bone had begun to char on the heated side as a result of the treatment. Upon examination of the marrow cavity it was found that the marrow was molten on one side and still very cold on the other. At its most extreme, on the radius, the temperature of the marrow on the heated side was 70°C and on the unheated side was still below freezing point. The average FFI value was 3.25.

General observations
Several general observations should be made at this point. Firstly, it seems that the experiments largely lived up to theoretical expectations. Fresh bones pro-

duced helical, smooth fractures with sharp angles and, on the whole, the harsher the treatment the bones were subjected to, the less this was the case. However, there were frequent exceptions. Some of these exceptions are probably due to the different level of effect various treatments had on different elements. They could also be due to variation in the author's fracturing technique. It certainly seems that the use of criteria, listed above, will not guarantee a correct diagnosis of degree of freshness at time of fracture for every individual specimen. In fact, some of the criteria can be at odds with each other. For instance, in the 'Two Weeks Frozen' experiment, the humerus had entirely helical fractures but a sizeable proportion, *c.* 40 per cent, of right-angle fracture. Conversely, the radius in the 'Five Hours in Oven' experiment had no right-angle fracture but no helical fracture either! There are other, similar, examples. It seems, how-ever, that the average result for each experiment was in line with expectations. It should be stressed that this methodology has not been devised for the study of individual fractures. It is an average result that would be important in assemblage analysis.

Secondly, it was surprising to find that the heated bones, particularly the boiled ones, were, in general, far more difficult to fracture than fresh specimens. Bonfield & Li (1966) demonstrated that bones '. . . exhibit a pronounced maximum in strength at 0°C'. Their experiments included elastic and plastic deformation as well as impact testing at a range of temperatures from –196 to 900°C. So why were the heated specimens in this set of experiments so difficult to fracture? One explanation might lie with the fact that Bonfield & Li (1966) carried out their experiments on thin, rectangular cut strips of bone rather than whole bones, as in this series of experiments. With a whole bone, a fracture line clearly has to travel round the whole circumference of the diaphysis before the marrow cavity can be properly accessed. The boiled and oven heated bones (apart from the 43-hour oven specimen which was incredibly brittle) seemed harder to break, not because they were not fracturing, but because the fractures were not meeting up to allow the shaft to break in two. When the shaft finally became broken fully around its circumference, it was because many fractures, often travelling in different directions, had met. This accounts for the jaggedness of some specimens. Helical fracture, in fresh bone, travels around the circumference of the diaphysis naturally, making access to the marrow cavity much easier.

Thirdly, some of the treatments used were clearly too harsh to ever be successfully employed before marrow extraction. Boiling for one hour resulted in marrow loss, whilst boiling for ten minutes resulted in melting the outside of the marrow, which might aid marrow extraction or improve consistency (see above). Heating the bone for one hour in the oven melted some of the marrow, whilst heating it for five hours resulted in most of it being liquid. Heating for 43 hours resulted in drying the marrow out completely. The application of radiant heat for a short time melted some of the marrow which, again, might ease marrow extraction. It was the author's own experience that it was easier to extract marrow if the outside part was molten.

Optimizing the Index

It can be seen from Table 6.2 that the Fracture Freshness Index, as calculated, has broadly classified the experiments according to expectations. The FFI value is, in general, higher the more severe the pre-fracture treatment is. The only real exception is the 'four weeks frozen' experiment, which has a lower value than the 'two weeks frozen experiment'. It may, however, be possible to improve the index. The way each of the criteria was scored may not lead to optimal results. Calculating the level of statistical correlation between each of the criteria and between the criteria and the average index will indicate if the criteria are in agreement. It will also indicate if one of the criteria is weak and in need of adjustment.

Pearson's coefficients of correlation have, therefore, been calculated. The correlation between criteria B (outline) and C (texture) is very high (0.9450, p = 0.000) and significant. A (angle), although having positive correlations with B and C (0.5223, p = 0.067 and 0.5290, p = 0.063 respectively), does not have particularly high levels of correlation. Both B and C correlate very well with the overall index (0.9706, p = 0.000 and 0.9741 p = 0.000 respectively), whilst A does not correlate quite so well (0.6663, p = 0.013). It seems, therefore, that criterion A, as it stands, might be a weak link in the index. The way it is scored might be improved.

In reviewing the way angle was scored, it was noted that fairly classic helical fractures could produce small amounts of right-angle fracture. As such, the scoring system for angle was altered to allow up to an estimated 10 per cent right angle fracture before a score of one was awarded. The result of this adjustment can be seen in Table 6.3 (the adjusted criterion A is denoted A_1 and the new index, $Index_1$). This resulted in very much improved levels of correlation. A_1 has a correlation of 0.7782 (p = 0.002) with

B and 0.6993 (p = 0.008) with C. The correlations between A_1, B and C and $Index_1$ were all both high and significant (0.8514 p = 0.000, 0.9808 p = 0.000 and 0.9622 p = 0.000 respectively). Further slight improvements were made possible by altering the scoring percentages for angle more still. However, very little advantage was gained and those scoring systems were ignored on the basis of being too difficult to assess through estimation. Dismissing the first 10 per cent of right-angle fracture, though, is easily achievable in analysis. It is concluded, therefore, that $Index_1$, due to its high level of internal agreement and ease of application, is the best index to use.

Discussion

Table 6.4 puts all the experiments in decreasing order of fracture freshness according to $Index_1$. They have been split into three groups. In the first group are the fresh and frozen experiments. It appears that freezing had little effect upon fracture type. All of these experiments have low index scores. As pointed out earlier, the 'four weeks frozen' experiment appears to be out of place. One would naturally expect the longer treatments to get the higher, less fresh scores. There is no explanation that can be offered for this, other than random error. Also, with $Index_1$, the '10 weeks frozen (not thawed)' experiment comes out as completely fresh. This may be more easily explained. Firstly, only two bones were used in this experiment, opening it up to more random error and, secondly, these bones were not defrosted before fracture like the other freezing experiments. The process of defrosting is likely to cause micro-cracks resulting in a higher FFI score.

The second group of experiments consists of experiments that replicate pre-marrow extraction likely to be encountered in ethnographic examples. All the treatments were found to melt some of the outer marrow, which would make it easier to extract. These treatments, which all involved mild heating, resulted in less fresh fracture features being present than was the case with the frozen experiments.

The final group consists of pre-fracture treatments unlikely to be used prior to marrow extraction. The 'one hour boiled' and the '43 hours in oven' experiments both resulted in complete loss of marrow. The 'five hours in oven' experiment resulted in some marrow loss and its complete liquefaction. This is not a desired effect for the extraction of marrow as encountered through the study of ethnographic examples. The heating of a bone next to a fire whilst it is still frozen might be a conceivable practice, but would be unlikely to be carried out in this way. In this experiment the marrow was molten on the outside but still frozen elsewhere. All these unlikely treatments produced much higher, more 'unfresh' FFI scores.

It seems that all sensible pre-marrow extraction treatments resulted in scores under three on the index. It appears that the FFI is very sensitive in picking up changes in fracture type caused by pre-fracture treatments, and there are few clear anomalies. The FFI can distinguish between fresh bones, those suffering mild treatments and those suffering more extreme treatments. The index, therefore, appears to be a useful tool in assemblage analy-

Table 6.3. *Mean criteria scores with adjusted criterion (A_1) and adjusted fracture freshness index by experiment.*

Experiment	A_1	B	C	$Index_1$
Fresh	0.14	0.14	0.00	0.28
2 Weeks Frozen	0.50	0.33	0.33	1.16
4 Weeks Frozen	0.25	0.00	0.25	0.5
20 Weeks Frozen	0.67	0.50	0.50	1.67
10 Weeks Frozen (not thawed)	0.00	0.00	0.00	0.00
1 Hour in Oven	0.75	0.75	0.75	2.25
5 Hours in Oven	0.75	1.50	1.50	3.75
43 Hours in Oven	1.00	2.00	2.00	5.00
10 Minutes Boiled	0.67	0.67	1.00	2.34
1 Hour Boiled	1.33	1.50	1.75	4.58
Radiant Heat (6 min., 1 side)	0.00	0.67	1.33	2.00
Radiant Heat (4 min., even)	0.50	0.75	0.75	2.00
10 wks Frozen, 10 min. Radiant Heat	1.00	1.00	1.25	3.25

Table 6.4. *Experiments in order of freshness of fracture according to adjusted Fracture Freshness $Index_1$.*

10 Weeks Frozen (not thawed) (0.00)
Fresh (0.28)
4 Weeks Frozen (0.50)
2 Weeks Frozen (1.16)
20 Weeks Frozen (1.67)

Treatments having a limited effect upon fresh fracture type. Fresh features dominate.

****

Radiant Heat, 4 min., even (2.00)
Radiant Heat, 6 min., 1 side (2.00)
1 Hour in Oven (2.25)
10 Minutes Boiled (2.34)

Treatments having some effect on fracture type, but there is still a majority of fresh features.

****

10 wk Frozen, 10 min. Radiant Heat, 1 side (3.25)
5 Hours in Oven (3.75)
1 Hour Boiled (4.58)
43 Hours in Oven (5.00)

Treatments having more severe effect. There is a majority of unfresh features.

sis that will be able to ascertain whether fracture type is consistent with marrow extraction techniques (a score under three) or not.

The goal of the experimental part of this study was to assess the validity of an index of fracture freshness in distinguishing between fractures consistent with marrow extraction and those that are not. This goal appears to have been successfully met. It should be stressed that, in statistical terms, the experimental sample sizes were quite small (although in practical terms they were quite large). As such, this study should only be seen as a pilot study into fracture types resulting from different marrow extraction techniques, which was intended to answer a specific question. This study would therefore be insufficient to support the identification of specific treatments, for instance. More detailed experimental work in the future, with the use of larger sample sizes, a more systematic study of the different levels of treatment and testing by a number of different analysts, would hopefully strengthen the methodology presented here and might allow for greater resolution of interpretation.

Example applications

Below, are two summarized examples of the application of the Fracture Freshness Index. The first is an examination of a high-altitude, Mesolithic site in the Italian Dolomites, the second is an analysis of a medieval Norse settlement site in Greenland. In both these cases not only bone-marrow exploitation, but also bone-grease exploitation, was being studied. In order to study rendering for bone grease one must assess the extent and nature of fragmentation as well as fracture type. The Fracture Freshness Index was principally designed to identify marrow extraction from bone shafts. The same criteria cannot be used to assess fracture types on cancellous bone comminuted during grease rendering. However, the FFI, as well as helping to identify marrow extraction (which commonly occurs before grease rendering), also tells one much about post-depositional taphonomy. Hence, if most shaft fracture is fresh then it strengthens the argument that high levels of fragmentation associated with grease rendering were the result of that practice rather than post-depositional attrition, which would have resulted in more dry and mineralized fractures of shaft fragments. The FFI is thus used below in arguments relating to both marrow extraction and grease rendering.

Mondeval de Sora is situated above the tree line, at 2100 m above sea level, in the Italian Dolomites. It is a cave site with occupation dating from the Sauvetarrian culture (seventh mil. BP) (Alciati *et al*. 1992), continuing through the Castelnovian (sixth mil. BP) and, after a hiatus, being re-used in the Copper Age. Its animal bone assemblage, which consists largely of ibex and red deer (Rowley-Conwy pers. comm.), is extremely fragmented. Almost all cancellous bone on this site has been reduced to small fragments and virtually no elements survive unfragmented (Outram 1998). Most of the larger fragments are shaft fragments. This fragmentation pattern is consistent with the fracturing of the bones for marrow, followed by the comminution of cancellous bone for the purpose of grease rendering. In order to corroborate this theory, it is essential to ascertain whether this fragmentation pattern was created whilst the bones were fresh. It is conceivable that it could be the result of density mediated, post-depositional attrition. Application of the fresh fracture index should provide the answer.

Figure 6.9 shows a break-down of the number of fragments attaining each of the FFI scores for one of the Sauveterrian contexts. Scores of three dominate but scores of zero, one and two are well-represented (particularly zero). Representation tails off through four, five and six. The mean FFI score for the sample is 2.52 (N = 300). Certainly not all of the assemblage was fractured fresh; there must have been some damage occurring after the bones were dried. However, the average is under three and there is a very strong representation of specimens scoring zero. This suggests that most of the fragmentation was due to fresh, or near-fresh, fracture and, as such, it seems very likely that the fragmentation pattern encountered is due to marrow extraction and bone-grease rendering.

Moving to the second example, the farmstead of Sandnes is the largest in the medieval Norse Western Settlement of Greenland. The occupation of the

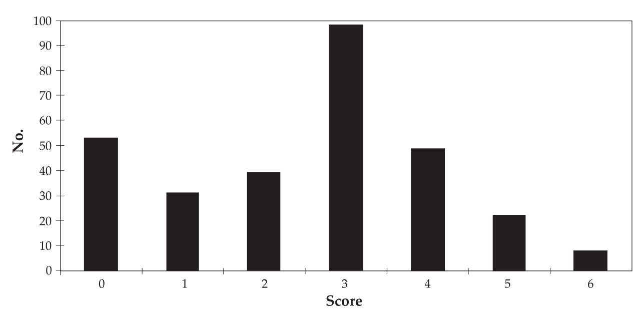

Figure 6.9. *A histogram showing the frequencies of FFI scores for a sample from the Sauveterrian layers of Mondeval de Sora, northern Italy.*

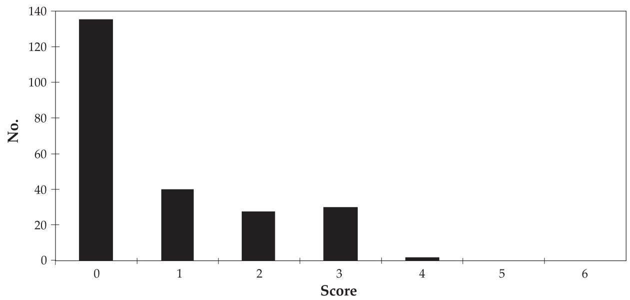

Figure 6.10. *A histogram showing the frequencies of FFI scores for a sample from the midden at Sandnes, Western Greenland.*

site started around AD 985 and ended by the close of the fifteenth century (Buckland *et al*. 1996). The inhabitants relied principally upon milk and meat from their domestic livestock, cattle, sheep, and goats, for their subsistence. This diet was subsidized by land-based hunting of seal, birds and caribou (McGovern 1985; Buckland et al. 1996). The climate was very harsh making this subsistence very marginal, and the Norse did not adopt Inuit subsistence methods and did not fish or hunt marine mammals by boat (Buckland et al. 1996). No fat-loving diptera (true flies) larvae were found in their middens. This led Buckland et al. (1996) to the conclusion that the subsistence stressed Norse had rendered all their bone waste for its valuable fat content.

The bone assemblage is indeed very fragmented (though not as extreme as Mondeval) and it is once again shaft fragments that dominate the larger size classes of fragments, with almost all cancellous bone, apart from the ribs, having been comminuted (Outram 1998; 1999; 2001). On this site the analysis of fracture freshness gave very clear results. Figure 6.10 shows the breakdown of index scores for the Sandnes midden sample. Scores of zero dominate by far and very few scores over three were recorded (and none over four). The mean Fracture Freshness Index value is 0.83 (N = 235). This leaves very little doubt that almost all fracture occurred on fresh bones. This, coupled with the entomological evidence and the fragmentation pattern strongly support the theory that the bones were being rendered for grease after marrow was extracted.

Conclusion

It has been experimentally demonstrated that a simple-to-apply index, based upon fracture outline, angle and texture, can discern between fracture types consistent with marrow extraction and those which are not. As well as working in theory, this method appears to work in practice. Its application has much strengthened the evidence for bone-fat rendering and marrow extraction at the above two sites. Furthermore, at the Greenlandic site, the conclusion suggested by interpretation of the bone fracture and fragmentation is corroborated by other forms of environmental evidence. The Fracture Freshness Index can also be used to examine other aspects of taphonomy, such as post-depositional attrition. If more detailed fracture experiments are carried out in the future, it is possible that more detailed interpretations might be ventured on the basis of fracture analysis.

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