

Experimental patterns of hammerstone percussion damage on bones: implications for inferences of carcass processing by humans

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Abstract:

The common occurrence of hammerstone percussion damage (pits, striae, notches and impact flakes) on the fossil limb bones of ungulates indicates that marrow extraction has been an important component of hominid butchery for over two million years. Beyond this level of basic inference, it would be behaviorally informative if three deeper aspects of marrow harvesting were understood more clearly: (1) whether inter-element patterns of bone fragmentation vary when processing intensity is held constant; (2) whether butcher investment in marrow extraction correlates positively with the number of percussion marks generated; (3) whether taphonomic effectors can be identified based on percussion mark morphology, frequency and placement. Some experimental work has been conducted previously in service of exploring these questions, but we set out here to address them explicitly through the analysis of a large sample of white-tailed deer (*Odocoileus virginianus*) limb elements fractured by hammerstone percussion. Our results indicate that (1) measures of bone fragmentation, which supposedly reflect processing intensity, are highly contingent on the research question being posed. This stresses the fact that researchers must be explicit in their definition of processing intensity. (2) In addition, hypothesized covariance between number of hammerstone blows and percussion mark frequencies are not met in our sample, corroborating previous conclusions of a lack of covariance between cutting strokes and cutmark frequencies. These results highlight the contingent nature of butchery mark production, and emphasize the need to investigate carcass resource exploitation by posing questions that do not rely on mark frequencies, but instead utilize other zooarchaeological measures. (3) Finally, our results—showing high incidences of impact notches and flakes created by direct anvil contact and “anvil scratches” created by direct hammerstone contact—suggest caution in using specific categories of percussion damage to infer their taphonomic effectors.

Keywords: Butchery; Carcass processing intensity; Bone fragmentation; Percussion marks

Article:

1. Introduction

Increasingly, zooarchaeologists have employed actualistic approaches to go beyond the basic inference that hominids have been involved in the butchery of large mammals for well over two million years [21,28], and have tried to understand the nature of carcass foraging adaptations more profoundly [e.g., 8,16,19,20]. Much of this work is focused on inferring carcass processing intensity [e.g., 1,3,36], while other approaches are concerned with identifying specific effectors applied to bones during butchery [e.g., 6,7,13,27,52]. Regardless of the specific question posed, a majority of the research is concerned with defleshing activities and thus deals specifically with cutmark data. However, another important component of butchery throughout prehistory has been the extraction of fat- and nutrient-rich marrow from the limb bones (i.e., humeri, radioulnae, femora, tibiae and metapodials; see [43]) of ungulates. Typically, hominids accomplished this by using unmodified cobbles, or hammerstones, to batter open those bones. Fortunately for the zooarchaeologist, this activity usually results in several classes of diagnostic taphonomic data, including percussion marks [e.g., 6,7,50,53], percussion notches

[e.g., 4,11,13,18,29], impact flakes [e.g., 13,18] and specific edge geometry of fractured bone specimens [2,18,46].

Recognizing the ubiquity of prehistoric marrow harvesting, we designed an experimental study to address three questions about this important aspect of hominid carcass foraging. First, do inter-element patterns of bone fragmentation vary when processing intensity is held constant? Zooarchaeologically, the assumption in most cases is that higher levels of fragmentation (however measured) reflect increased processing intensity [e.g., 17,25,26,35,37-40,49]. Second, does butcher investment in marrow extraction correlate positively with the number of percussion marks generated? Researchers have made a similar assumption in studies of cutmark creation, and in so doing assume that mark frequencies (however quantified) increase with increasing levels of processing intensity [e.g., 1,5,23,26,36,41]. Third, can taphonomic effectors be identified based on percussion mark morphology, frequency and placement? Percussion marks take a variety of forms, and the functional terminology used to describe some of these forms (e.g., “anvil scratches” [50]) implies their creation by specific effectors (see below). However, we are unaware of any experimental study prior to ours that has tested these relationships between mark form and effectors. We believe that data we present regarding these three issues will usefully supplement those data on cutmarks generated previously to address comparable questions regarding carcass defleshing.

2. Materials and methods

2.1. Experimental sample and protocol

Our sample consists of all bone fragments > 1 cm in maximum dimension generated when 36 humeri and 38 radii of white-tailed deer (*Odocoileus virginianus*) were broken with hammerstones in order to extract marrow. We chose white-tailed deer bones for two reasons. First, they are locally abundant and were readily available to us courtesy of K.W. Deer Processing (Bloomington, Indiana, USA) during the Fall 2004 hunting season. Second, white-tailed deer are medium-sized artiodactyls (Size Class 2 in Brain’s [10] well-known classificatory scheme), this being relevant because medium-sized artiodactyls predominate in many archaeofaunas worldwide. While we were able to generate some data on other limb bones, we were forced to concentrate on humeri and radii because those were the only limb bones available to us that were regularly intact after processing at K.W. (femora were sectioned transversely multiple times along their lengths in making round steaks, and tibiae and metapodials were usually broken during butchery). We do, however, believe that the limited choice of humeri and radii still gives us a good representative sample of a minimally fractured element (humerus) and an extensively fractured element (radius) (see discussion below).

Metal knives were used to deflesh bones, with processors at K.W. removing the major muscle masses for their clients and TRP and CPE subsequently removing any flesh that still adhered to anticipated impact surfaces. Periosteum was never removed before hammerstone percussion. We used two hammerstone—anvil sets for our experiments, one a “coarse” set, the other a “smooth” set (Fig. 1). The coarse set consists of two grainy sandstone blocks, the hammerstone being rectangular and weighing 698.3 g. The smooth set consists of two heavily rolled quartzite cobbles, with completely smooth surfaces, the hammerstone being oblong and weighing 610.8 g. None of the tool surfaces was intentionally modified. Following the methodology of Blumenschine and Selvaggio [7, p. 19], “Bones were broken to an extent sufficient to remove all marrow with a 12-inch pharmaceutical spatula.” For the humeri, this was accomplished by resting the lateral shaft of each across the summit of the anvil and directing the hammerstone impact at its medial midshaft [7,13]. For the radii, each of which was still attached to its ulna, breakage was accomplished by resting their lateral sides on the anvil “so that the ulna[e] could serve to steady the bone[s], and hammerstone impact occurred on the medial face[s]” [7, p. 22]. Blumenschine and Selvaggio [7, p. 22] continue that “[b]ecause the shafts of radii are relatively broad from the lateral to the medial side, greater force was required to fracture the bone than if impact occurred on the relatively flat anterior face”. In our experience, and in agreement with the logic of Blumenschine and Selvaggio, the easier method of breaching the anterior radius surface usually drives many small bone fragments into the marrow at the point of impact (which is undesirable from the viewpoint of a consumer) and otherwise results in two large epiphyseal plus shaft specimens that retain their complete original diaphyseal circumferences. Maintaining the complete and very narrow circumferences of Size Class 2 radii is at odds with the goal of

efficient and complete marrow extraction. Hence, the more laborious medial impact method is preferred, and the dichotomy between a minimally fractured element (the humerus) and an extensively fractured element (the radius) is explained.

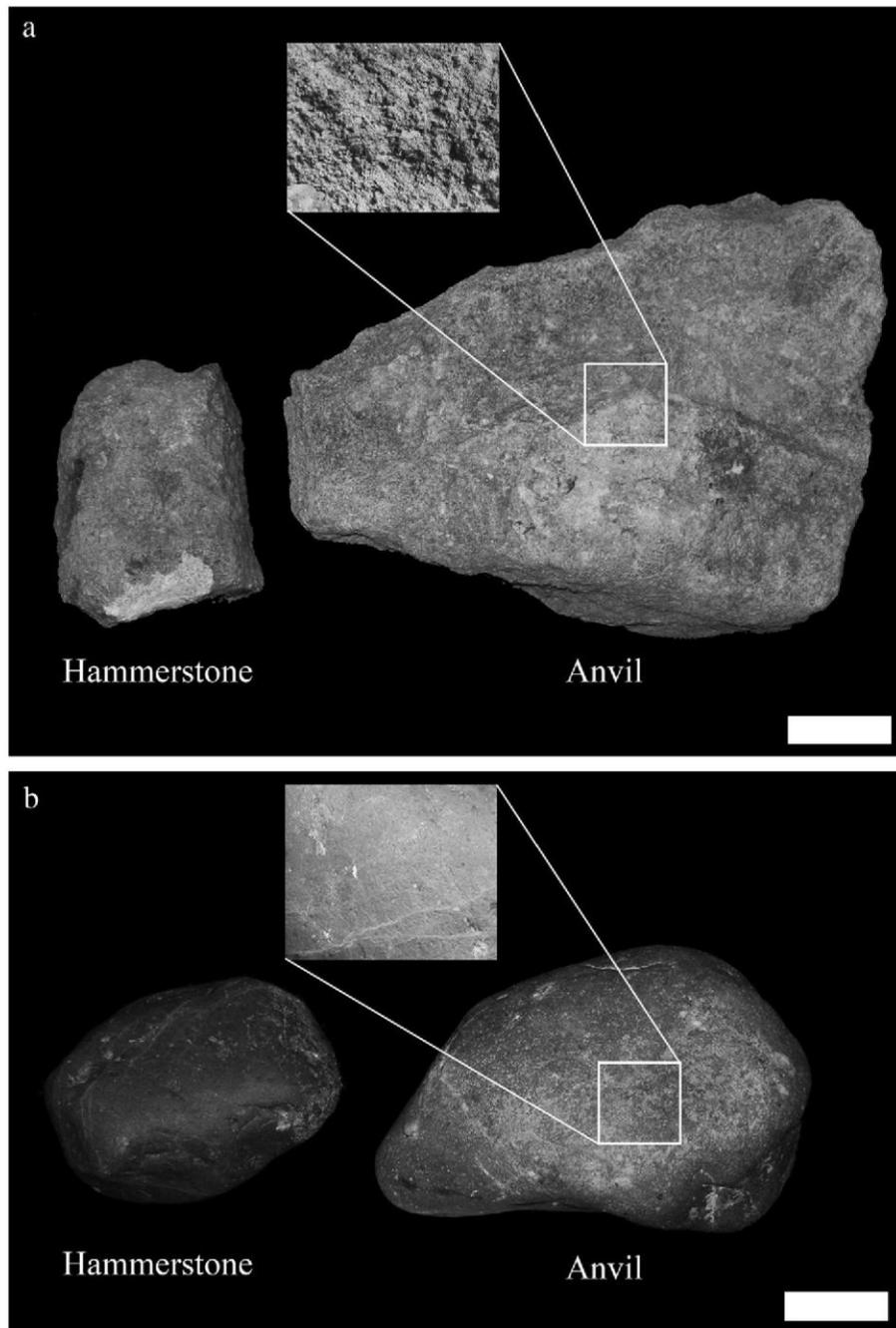


Fig. 1. Tool sets used in the hammerstone experiments. A total of 39 whole bones were broken open using the coarse hammerstone and anvil (a), while a total of 35 were fractured with the smooth tools (b). See text and Table 3 for details of tool raw materials, masses and the resultant fractured bone sample associated with each. Bar scale = 5 cm.

After a bone was breached sufficiently for marrow extraction, all resultant fragments (including those that adhered to the hammerstone and anvil) were collected, bagged in cheesecloth and then boiled together until clean. Each fragment was labeled with an experimental episode number (one per whole element) and an individual specimen number (e.g., IMP/072/ 3 = Impact experiment/72nd experimental episode/specimen 3). All specimens were then examined with 10× hand lenses under a strong oblique light source by both authors [9]. A consensus opinion was reached for each mark asserted to be hammerstone damage before it was recorded as such in the database.

2.2. Processing intensity and butcher investment

In a general sense, zooarchaeologists expect increased processing intensity to be reflected by (1) the utilization of lower-ranking carcass parts; and (2) the extraction of multiple carcass tissues (e.g., butchering a carcass or carcass part not only for meat but also for marrow and grease) and/or increased investment in the removal of one particular carcass tissue (e.g., filleting a carcass or carcass part not only for large muscle masses but also for small flesh scraps). In this study, we attempted to isolate the variables responsible for patterns of bone fragmentation by holding processing intensity constant. Thus, differential fragmentation cannot be attributed to (1) the processing of multiple carcass resources, as all elements were processed solely for marrow; and (2) the extent to which each element was processed, as all elements were processed to the minimum extent required to breach the medullary cavity for complete marrow extraction. The number of impact blows required to expose the medullary cavity is used here as a proxy of butcher investment in marrow extraction.

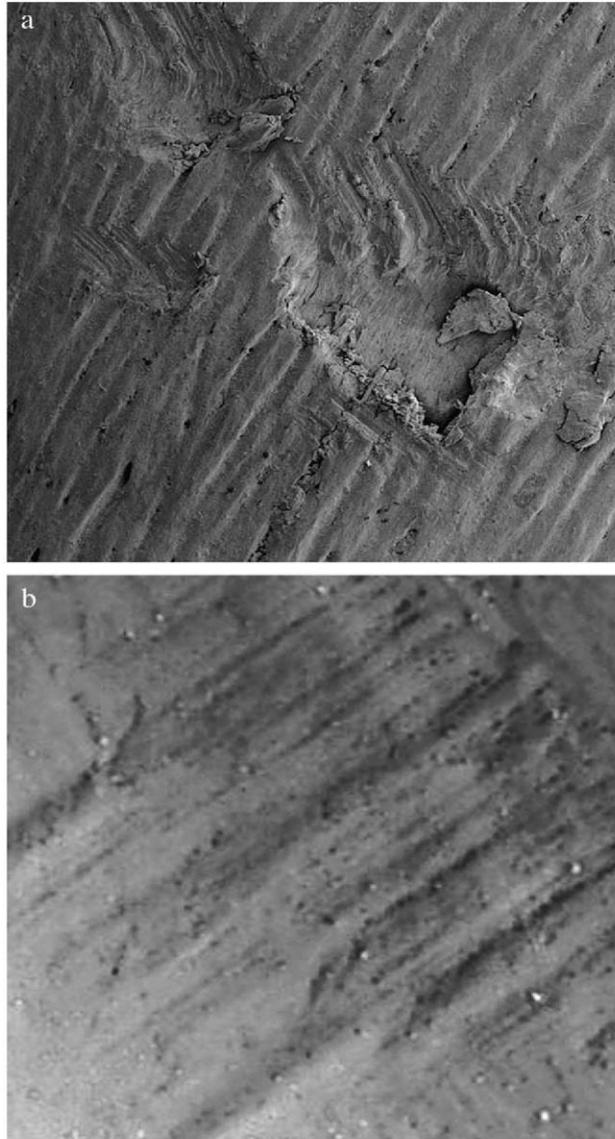


Fig. 2. Microscopic images of the two major classes of surficial percussion mark. Note patches of microstriations emanating from the pits (a). In some cases, such microstriation patches are deeply set, depressed through multiple layers of lamellae, forming a striae-covered basin that is considered a distinct sub-class of pit. Both types of pits are distinguishable from striae fields (b), which are composed of extremely shallow, subparallel scratches that usually cover relatively expansive lengths of cortical surface, between 5 and >50 mm. Image (a) is courtesy of M. Domínguez-Rodrigo.

2.3. Terminology and attributes of investigation

We investigated several variables in our experimental sample relevant to understanding marrow harvesting by early hominids. Before discussing these, however, we define several important terms:

- (1) Impact event refers to a single contact between a hammer-stone and a bone resting on an anvil. In some cases, a bone was each breeched under a single impact event, while other bones required multiple impact events to open.
- (2) Anvil side refers to that surface of a limb bone rested against an anvil during a hammerstone impact event.
- (3) Hammerstone side refers to that surface of a limb bone contacted by a hammerstone during an impact event.
- (4) Percussion marks refer to “pits and striae, which are sometimes but not always associated with percussion notches [see below]. Diagnostic morphology and configuration of percussion pits and striae are described and illustrated by Turner [50] and Blumenschine and Selvaggio [6,7]. Pits are often closely associated with and/or have emanating from the patches of striae that result from slippage of stone against bone during impact events” ([44, p. 215]; adapted from [6]) (Fig. 2).

We follow White [53] in dividing percussion marks into two major classes based on their morphologies: striae fields (called “anvil scratches” by Turner [50]) and pits. Like White [53, p. 151], our “analysis keeps these [damage types] separate, with the recognition that they are part of the same phenomenon and may overlap on the bone”.

- (5) Percussion notches refer to “semicircular- to arcuate-shaped indentations on fracture edges with corresponding negative flake scars on medullary surfaces [of limb bones]” [18, p. 724] (Fig. 3).
- (6) Epiphyseal specimens refer to hammerstone fractured limb bone specimens that retain part or all of a single epiphysis and some length of attached shaft. These specimens usually, but not always, retain their complete original diaphyseal circumferences. In some instances complete bones were of subadult status and therefore had one or two epiphyses that were not yet fused at the time of the animal’s death. These naturally detached epiphyses are distinguished from epiphyseal specimens as defined here and were removed from our analyses. Here, a subadult epiphyseal specimen is a proximal or distal length of shaft that retains an epiphyseal plate instead of a fused epiphysis.
- (7) Shaft cylinders refer to diaphyseal fragments that lack epiphyses but retain 100% of their original circumferences (see also [4, p. 171]).
- (8) Shaft splinters refer to shaft fragments > 1 cm in maximum dimension that are produced by hammerstone percussion. They lack any attached epiphyseal portion. They also lack the technical attributes of impact flakes (as described below), and retain < 100% of their original diaphyseal circumferences (see also, [53, p. 132]).
- (9) Impact flakes refer to shaft fragments produced by hammerstone percussion that “display the same basic technical attributes of percussion as occur on flakes...of knapped fine-grained stone: (1) flakes possess a platform at the impact point and a bulb of percussion below the platform; [and] (2) they sometimes show ‘ripple’ marks and/or hackle (stress) marks originating at or near the platform or bulb...” [24, p. 21] (Fig. 4). Impact flakes lack any attached epiphyseal portions and their complete original diaphyseal circumferences.
- (10) Fracture angle refers to that “angle formed by the fracture surface and the bone cortical surface” [51, p. 34]. This angle was measured at its midpoint using a goniometer for each longitudinal, transverse and oblique (with reference to the specimen long axis) fracture plane (following [2,46]).

For each fractured element, we recorded the following information (many, but not all, of these variables are adapted from Bunn [13] and Blumenschine and Selvaggio [7]):

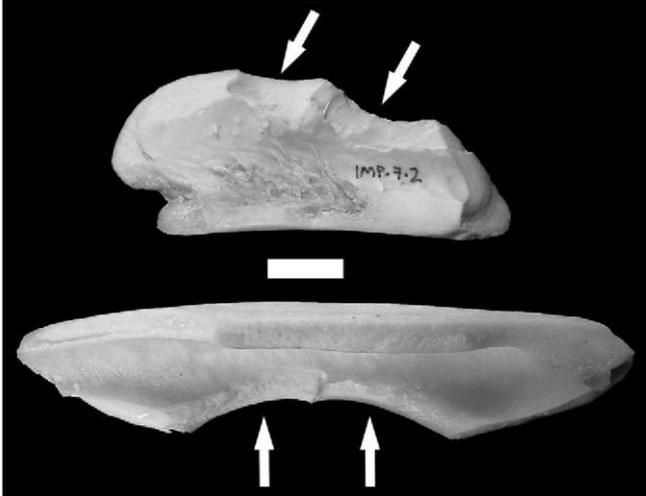


Fig. 3. Examples of typical percussion notches in the experimental sample. Note the variable sizes but consistent presence of negative flake scars (or inner conchoidal percussion scars; [53]), indicated by the arrows, on the medullary surfaces of the two bone specimens. Bar scale = 1 cm.

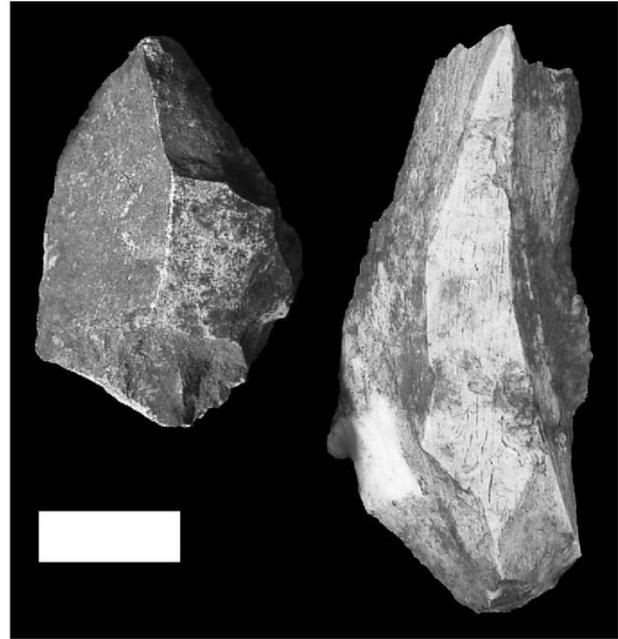


Fig. 4. Examples of typical impact flakes. Note the cortical platforms and prominent bulbs of percussion emanating from below those platforms. Bar scale = 1 cm.

- (1) Number of blows required to expose the medullary cavity for complete marrow extraction with the 12-inch pharmaceutical spatula (see above).
- (2) Number of epiphyseal specimens produced.
- (3) Number of cylinders produced.
- (4) Number of shaft splinters produced.
- (5) Number of impact flakes produced.
- (6) Types (pits versus striae fields), frequency and distribution of percussion marks per specimen type (2-5 above). As the name suggests, striae fields [53] are more diffuse in their morphology than are percussion pits, with variable widths and lengths, but we determined individual incidences by a minimum 5 mm break between individual striae that comprise each field (Fig. 2b).
- (7) Number and distribution of percussion notches per specimen type (2-5 above).
- (8) Length and width maxima of each epiphyseal specimen, cylinder, shaft splinter and impact flake produced.
- (9) Remaining diaphyseal circumference of each specimen produced. Following Bunn [12], we assigned a value of 100%, < 100% but > 50%, or < 50% (see [46,47]).
- (10) Fracture angle for each measurable fracture plane on each specimen.

3. Results and discussion

3.1. General characteristics of the assemblage

Table 1 summarizes basic characteristics of our experimentally produced assemblage of hammerstone fractured bones.

Table 1
General characteristics of the hammerstone fractured bone sample^a

Specimen type	Total NISP (%)	Total NISP (%) with at least one percussion mark
Humerus (MNE = 36)	472 (100.0%)	100 (21.1%)
Epiphyseal (no notch)	66 (13.9%)	46 (69.7%)
Epiphyseal (notch)	6 (1.3%)	4 (66.7%)
Cylinder	0 (0.0%)	0 (0.0%)
Splinter (no notch)	352 (74.6%)	38 (10.8%)
Splinter (notch)	14 (2.9%)	8 (57.1%)
Impact flake	34 (7.2%)	4 (11.8%)
Radius (MNE = 38)	811 (100.0%)	112 (13.8%)
Epiphyseal (no notch)	89 (10.9%)	42 (47.2%)
Epiphyseal (notch)	2 (0.2%)	1 (50.0%)
Cylinder	1 (0.1%)	1 (100.0%)
Splinter (no notch)	674 (83.1%)	65 (9.6%)
Splinter (notch)	5 (0.6%)	0 (0.0%)
Impact flake	40 (4.9%)	3 (7.5%)
Humerus + radius (MNE = 74)	1283 (100.0%)	212 (16.5%)
Epiphyseal (no notch)	155 (12.1%)	88 (56.8%)
Epiphyseal (notch)	8 (0.6%)	5 (62.5%)
Cylinder	1 (0.0%)	1 (100.0%)
Splinter (no notch)	1026 (80.0%)	103 (10.0%)
Splinter (notch)	19 (1.5%)	8 (42.1%)
Impact flake	74 (5.8%)	7 (9.5%)

^a NISP = number of identified specimens.

The predominant type of specimen we generated is the shaft splinter, with a mean average length of 29.6 mm (Fig. 5). The distribution of diaphyseal completeness in our sample agrees with a pattern documented by Marean et al. [34] in experimental and archaeological assemblages that received full recovery and analytical attention, with a vast majority of specimens retaining <50% of their original circumferences (Fig. 6).

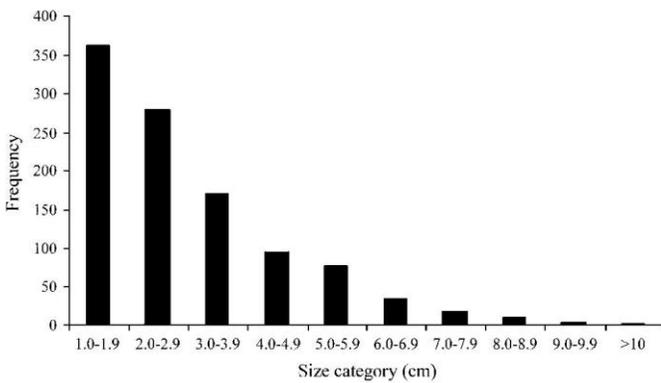


Fig. 5. Histogram of shaft splinter sizes in the experimental sample.

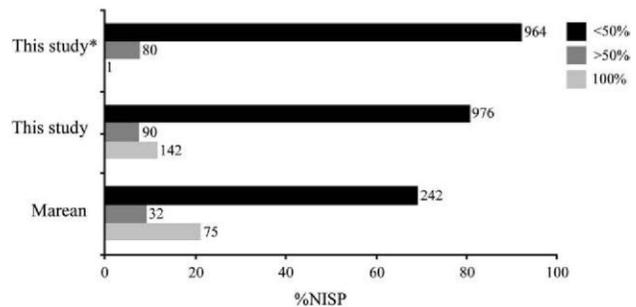


Fig. 6. The percentage of Bunn's [12] limb bone circumference types on limb bone fragments from our sample of fractured deer bones (top two sets of bars, This study* and This study) and Marean's [34] sample of hammerstone broken sheep bones. Note the strong and consistent pattern across all samples in which a vast majority of specimens preserve <50% of their original diaphyseal circumferences. The second rank of specimens that retain 100% of their circumferences in our (This study) and Marean's samples (bottom two sets of bars) is only due to their inclusion of epiphyseal specimens. When epiphyseal specimens were removed from our sample (top set of bars, This study*) specimens with 100% circumferences are also eliminated.

Notchless splinters predominate, followed in frequency by notchless epiphyseal specimens, impact flakes, notched splinters, notched epiphyseal specimens and cylinders. The disparity in frequencies of total impact flakes (n = 74) and notched specimens (n = 27) demands explanation since, in theory, every impact flake should have a corresponding notch from which it was detached. We suspect the discrepancy in frequencies exists for at least two reasons. First, a notch generated early in a series of impact events can be obliterated by subsequent blows needed to completely breach a bone. In contrast, detached flakes are usually not destroyed in such a case, resulting in a higher number of flakes and fewer notches. Second, many specimens preserve features that Capaldo and Blumenschine [18] term "pseudo-notches". These features are actually notches, in that we are absolutely positive they resulted from dynamic impact imparted by a hammerstone, but they do not possess the classic or "normal" morphology (as defined by Capaldo and Blumenschine [18]) that we demand when assigning a notch in a zooarchaeological sample to the hammerstone-generated category (Fig. 7). This is

because all zooarchaeological specimens are, by definition, of unknown origin and it is our task to infer those origins as accurately as possible, but we are maximally conservative in our assignments of bone damage.

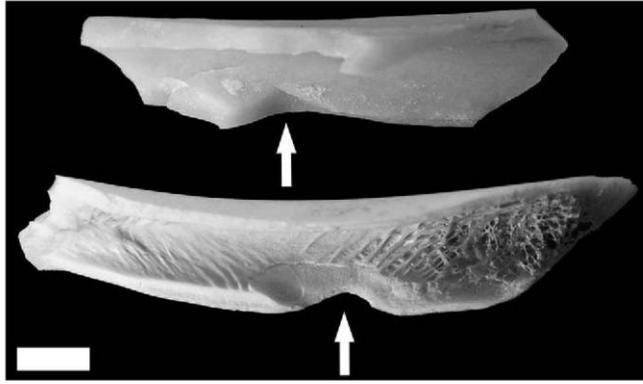


Fig. 7. Medullary surfaces of limb bones, illustrating a “pseudo-notch” (indicated by the arrow) on a radius specimen (top) compared to an unambiguous notch (indicated by the arrow) on a humerus specimen (bottom). Note the lack of a negative flake scar on the “pseudo-notch” and the presence of one on the notch. Additionally, the “pseudo-notch” lacks definitive points of inflection, while the true notch has clearly visible ones that bound it. Conservatively, the “pseudo-notch” would *not* be recorded as percussion damage in an archaeological assemblage. Bar scale = 1 cm.

Most of the “pseudo-notches” in our sample occur on radius specimens. We suspect that this has to do with the fact that our hammerstone blows landed on the sharp-edged medial border of each radius and the force generated was absorbed across its sharp-edged lateral border that rested on the anvil. The multiple blows that were incurred by radii in this fashion resulted in many fragments that possessed unexpected morphologies. Of the 996 fracture angles we measured on radius specimens, 167 (16.8%) were right or near-right angles (i.e., 85–95°), types of breaks usually associated with dry bone fracture. In contrast, specimens deriving from the more easily fractured and tubular-shaped humeri possess a greater proportion of measured angles that conform to that expected on fresh broken bone. Only 66 (10.6%) of 621 angles we measured on humerus specimens were between 85° and 95°, a difference with the radius sample that is statistically significant ($\chi^2 = 16.229$, 1 d.f., $P < 0.001$) (Fig. 8). It seems that sharp angles on edges of D-shaped radii acted mechanically to truncate the complete carry-through of notches with smooth, readily apparent release surfaces. Again, this was not generally the case with the more circular and thinner-walled humeri, which yielded many more spirally shaped fragments, associated stereotypically with green bone breakage. The greater disparity between total impact flakes and total notched specimens for radii (40 versus 7, respectively) compared to the difference for humeri (34 versus 20, respectively) provides support for this hypothesis. Based on anatomical considerations of whole bones, we predict that large samples of hammerstone broken femora and tibiae should conform, respectively, to the humerus and radius pattern documented here.

3.2. Bone fragmentation and processing intensity

Three standard measures of bone breakage indicate that the radii are more highly fragmented than are the humeri. First, there is a significant difference between the humerus and radius samples in the proportion of epiphyseal (humerus $n = 74$; radius $n = 91$) to non-epiphyseal specimens (humerus $n = 401$; radius $n = 720$) in each ($\chi^2 = 5.097$, 1 d.f., $P < 0.01$). Second, fragmentation ratios (NISP:MNE)¹ also indicate greater comminution of radii (humeri = 13.1; radii = 21.3). Finally, the distribution of fragment sizes indicates higher fragmentation for radii (Fig. 9). These patterns are unexpected given that processing intensity as defined by the minimum effort required to breach the medullary cavity for complete marrow extraction was held constant. The only variable that can explain the differential fragmentation is that more effort was required to process radii. It required a total of 226 blows (mean per individual radius = 6, range 2e15) to expose the medullary cavities of the thick-walled radii, while only 73 total blows (mean per individual humerus = 2, range 1e4) were required to accomplish the same result with a similar number of the larger-chambered humeri.

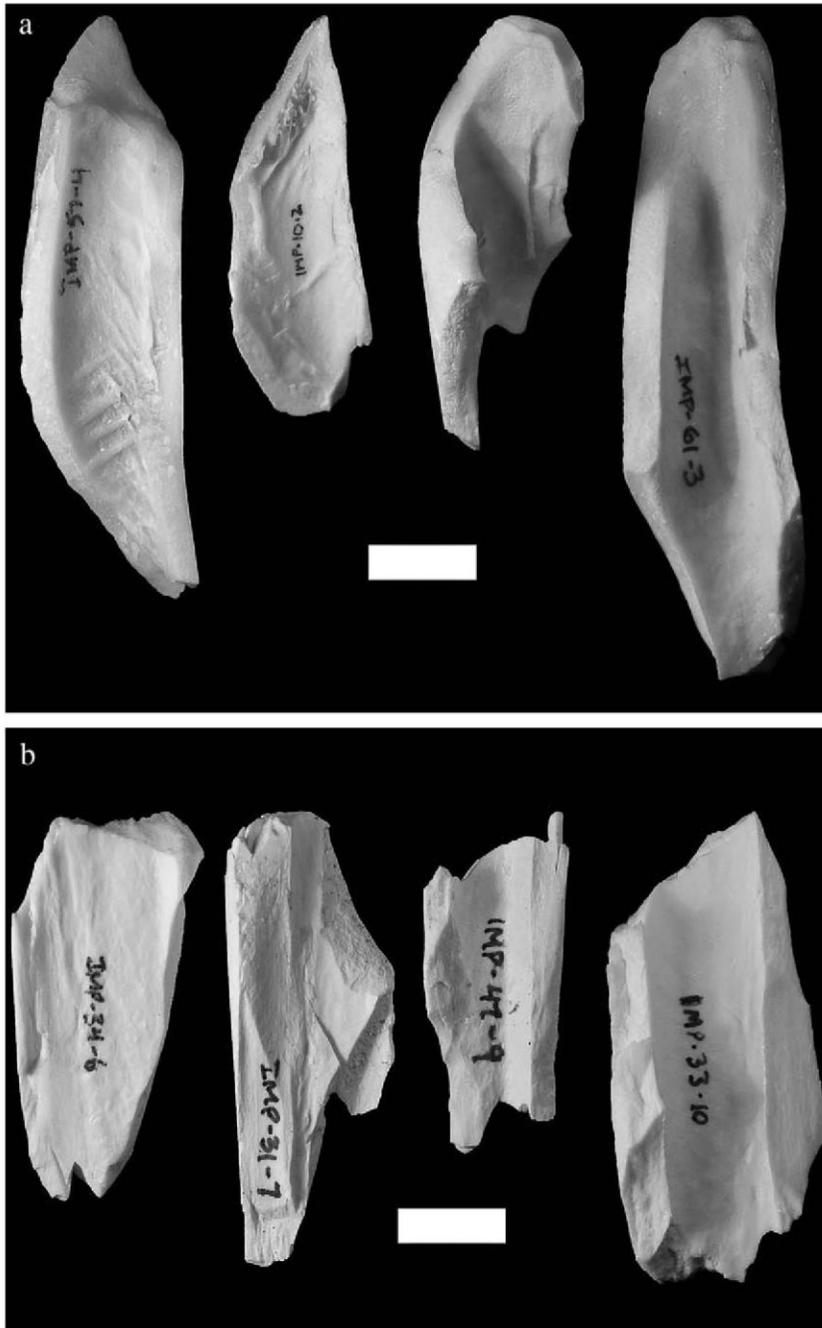


Fig. 8. Illustrative examples of common spirally fractured specimens in the humerus sample (top) compared to a marked right-angled morphology of many specimens in the radius sample (bottom). Bar scale = 1 cm.

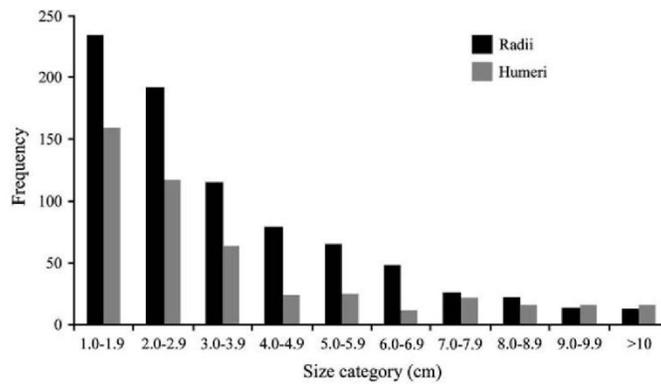


Fig. 9. Inter-element distribution of fragment sizes for the radius and humerus.

Table 2

Frequency and anatomical distribution of percussion mark types (striae fields and pits) in the hammerstone fractured bone sample^{a-c}

Total NISP with at least one percussion mark	Total striae fields		Total pits ^d		Total striae fields + pits	
	Hammer	Anvil	Hammer	Anvil	Hammer	Anvil
Humerus, 100	9	22	46	95	55	117
Epiphyseal (no notch), 46	6	12	21	59	27	71
Epiphyseal (notch), 4	1	1	7	1	8	2
Cylinder, 0	0	0	0	0	0	0
Splinter (no notch), 38	1	5	11	25	12	30
Splinter (notch), 8	1	4	6	5	7	11
Impact flake, 4	1	0	0	5	1	5
Radius, 112	7	35	49	83	56	118
Epiphyseal (no notch), 42	1	25	18	34	19	59
Epiphyseal (notch), 1	0	1	0	1	0	2
Cylinder, 1	0	1	0	2	0	3
Splinter (no notch), 65	6	8	29	46	35	54
Splinter (notch), 0	0	0	0	0	0	0
Impact flake, 3	2	0	0	0	2	0
Humerus + radius, 212	16	57	95	178	111	235
Epiphyseal (no notch), 88	7	37	39	93	46	130
Epiphyseal (notch), 5	1	2	7	2	8	4
Cylinder, 1	0	1	0	2	0	3
Splinter (no notch), 103	7	13	40	71	47	84
Splinter (notch), 8	1	4	6	5	7	9
Impact flake, 7	3	0	0	5	3	5

^a NISP = number of identified specimens.

^b Table does not include three striae field marks and 16 pits that could not be attributed confidently to either hammerstone or anvil damage.

^c Hammer refers to the bone surface contacted directly with the hammerstone during impact events; anvil refers to the bone surface in direct contact with the anvil during impact events.

^d Includes those pits with and without emanating striae.

3.3. Percussion mark types, distributions and frequencies by tool sets

Percussion marks occur on every type of specimen in our experimental sample. As summarized in Table 2, the most common type of percussion mark is pitting (79.2%). Of the 346 percussion marks that could be assigned to either the hammerstone or anvil side of a specimen, 235 (67.9%) are preserved on the anvil side. There is a higher frequency of striae field marks on bone surfaces that were rested against anvils ($n = 57$) than on surfaces directly impacted by hammerstones ($n = 16$) ($\chi^2 = 4.364$, 1 d.f., $P < 0.05$). However, it is important to note that hammerstone contact was still responsible for a sizeable proportion of striae field marks, accounting for 22% of them. This observation lessens the diagnostic value of striae fields for discerning positional information of bones during episodes of hominid marrow harvesting. Thus, zooarchaeologists should be cautious about the use of Turner's [50] functional term "anvil scratches" to describe this type of damage. Similarly, against conventional expectations, our data show concurrence between the frequency of notches and impact flakes generated by direct contact with both hammerstones and anvils during impact events. For those notches that could be identified as deriving from the hammerstone-receiving or anvil-resting side of a bone, 17 occur on the former surfaces and 16 occur on the latter.

In addition, although there is a statistically significant difference in mean percussion mark frequency per marked specimen imparted by smooth (mean = 2.8 marks) and coarse (mean = 6.4 marks) tool sets (Mann-Whitney $U = 203.0$, $Z = -3.11$, $P = 0.002$; Table 3), it is difficult to envisage actual archaeological situations in which this information might be usefully applied. It is true that among the world's earliest archaeological traces there are at least two occurrences, at Bouri (Ethiopia) [28] and at some sites on the Koobi Fora Ridge (Kenya) [14], which preserve butchered bones without stratigraphically associated lithics. However, these assemblages are too small to dichotomize the percussed specimens in each into moderately and intensely marked categories, and then apply our results to infer the broad types of hammerstone raw materials employed by hominids there. Even in the common situation of a Stone Age site with samples of unmodified or minimally modified cobbles of unknown prehistoric function, it seems unlikely that the associated percussion marked bone samples will be

sufficient to detect a statistically significant difference in mark frequencies that could be attributable to differences in cobble raw materials (e.g., of > 20,000 limb bone shaft fragments we have examined in depth from Swartkrans Cave, South Africa, less than 70 preserve percussion marks [44e48]).

Table 3
Distribution of percussion marks broken down by tool set type^{a,b}

Tool set type	Specimen type	Total NISP (%)	Total NISP (%) with at least one percussion mark
Smooth	Humerus (MNE = 16)	191 (100.0%)	38 (19.9%)
	Epiphyseal (no notch)	31 (16.2%)	22 (70.8%)
	Epiphyseal (notch)	1 (0.5%)	1 (100.0%)
	Cylinder	0 (0.0%)	0 (0.0%)
	Splinter (no notch)	140 (73.3%)	10 (7.1%)
	Splinter (notch)	7 (3.7%)	5 (71.4%)
	Impact flake	12 (6.3%)	0 (0.0%)
	Radius (MNE = 19)	338 (100.0%)	32 (9.5%)
	Epiphyseal (no notch)	44 (13.0%)	15 (34.1%)
	Epiphyseal (notch)	2 (0.6%)	1 (50.0%)
	Cylinder	1 (0.3%)	1 (100.0%)
	Splinter (no notch)	272 (80.5%)	15 (5.5%)
	Splinter (notch)	4 (1.2%)	0 (0.0%)
	Impact flake	15 (4.4%)	0 (0.0%)
	Humerus + radius (MNE = 35)	529 (100.0%)	70 (13.2%)
	Epiphyseal (no notch)	75 (14.2%)	37 (49.3%)
	Epiphyseal (notch)	3 (0.6%)	2 (66.7%)
	Cylinder	1 (0.2%)	1 (100.0%)
	Splinter (no notch)	412 (77.9%)	25 (6.1%)
	Splinter (notch)	11 (2.1%)	5 (45.5%)
	Impact flake	27 (5.1%)	0 (0.0%)
Coarse	Humerus (MNE = 20)	281 (100.0%)	62 (22.1%)
	Epiphyseal (no notch)	35 (12.5%)	24 (68.6%)
	Epiphyseal (notch)	5 (1.8%)	3 (60.0%)
	Cylinder	0 (0.0%)	0 (0.0%)
	Splinter (no notch)	212 (75.4%)	28 (13.2%)
	Splinter (notch)	7 (2.5%)	3 (42.9%)
	Impact flake	22 (7.8%)	4 (18.2%)
	Radius (MNE = 19)	473 (100.0%)	80 (16.9%)
	Epiphyseal (no notch)	45 (9.5%)	27 (60.0%)
	Epiphyseal (notch)	0 (0.0%)	0 (0.0%)
	Cylinder	0 (0.0%)	0 (0.0%)
	Splinter (no notch)	402 (84.9%)	50 (12.4%)
	Splinter (notch)	1 (0.2%)	0 (0.0%)
	Impact flake	25 (5.3%)	3 (12.0%)
	Humerus + radius (MNE = 39)	754 (100.0%)	142 (18.8%)
	Epiphyseal (no notch)	80 (10.6%)	51 (63.8%)
	Epiphyseal (notch)	5 (0.7%)	3 (60.0%)
	Cylinder	0 (0.0%)	0 (0.0%)
	Splinter (no notch)	614 (81.4%)	78 (12.7%)
	Splinter (notch)	8 (1.1%)	3 (37.5%)
	Impact flake	47 (6.2%)	7 (14.9%)

^a NISP = number of identified specimens.

^b The smooth tool set consists of two heavily rolled quartzite cobbles; the coarse tool set consists of two sandstone blocks.

3.4. Overall frequencies of percussion marks and butcher investment

Taken as a whole, there is a statistically significant negative correlation between number of hammerstone blows and percussion mark frequency ($r_s = -0.234$, $P = 0.045$) (Fig. 10). This finding contradicts a prediction of positive co-variation between those variables, and agrees with Egeland's [22] findings on a sample of bones butchered experimentally with stone flakes. Analysis of that sample also failed to result in the expected correlation between frequency of cutting strokes and frequency of cutmarks. There are several uninvestigated factors that could be responsible for the unexpected results in the current study, including the variable amounts and thicknesses of adhering soft tissues on individual whole bones. For example, 34.2% ($n = 13$) of the total

radius MNE preserve no percussion marks at all, while only 11.1% ($n = 4$) of the total humerus MNE show no percussion marks. We observed a difference in our sample with markedly thicker periosteum on the radii than on the humeri. Periosteum and residual musculature not only had the potential to cushion bones from receiving percussion marks under direct blows, but they also caused significant slippage of specimens during some impact events. In such cases, many of the recorded blows were glancing or deflected rather than concentrated incidences of impact, unlikely to impart marks. Such observations stress the contingent and fortuitous nature of butchery mark production [33]. This does not mean that butchery marks, whether cutmarks or percussion marks, are inexplicable; rather it means that they are an incidental byproduct of hominid behaviors that are unintended. It also means that we need to search much deeper for correlations between mark frequencies and potential causal variables [33].

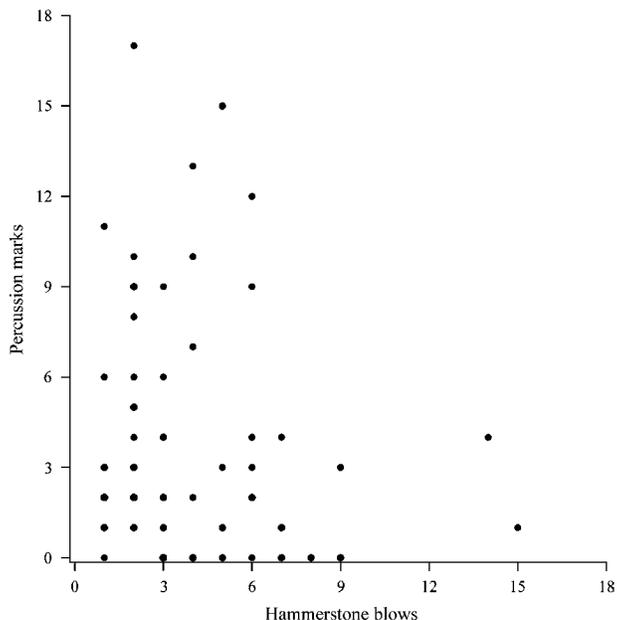


Fig. 10. Bivariate scatterplot showing the relationship between number of hammerstone blows and percussion mark frequency in the complete experimental sample.

Given the preceding, it is of note that percussion mark frequencies mirror closely in some ways Egeland’s [22] data on cutmark frequencies. Of the total MNE of 74 in our sample, 57 (77.0%) display at least one percussion mark. Similarly, Egeland [22] found that 87% of the total MNE in his sample of defleshed limb bones preserves at least one cutmark. Egeland’s [22] sample is composed of larger, Size Classes 3 and 4, ungulates than ours—but we feel fairly comfortable in suggesting that zooarchaeologists might expect that 75-85% of the total limb bone MNE to display surficial butchery marks in an archaeofauna composed of medium to large sized ungulates and processed completely by humans. This measure is a very general assessment of a very complicated occurrence. We are simply suggesting a baseline that needs to be corroborated or contradicted case-by-case using multiple lines of independent zooarchaeological and taphonomic inquiry.

4. Conclusions

Our results confirm a growing awareness that an array of confounding variables, impossible to control over time and geography or to measure archaeologically, hold the potential to obscure meaningful linkages between butchering intensity and bone surface damage [30,32,33]. This is an important insight that will hopefully prompt researchers to adjust the questions they ask of the zooarchaeological record to those that might be more productively explored. For example, we remain convinced that anatomical placement of cutmarks on archaeofaunal specimens is useful for inferring the timing of hominid access to animal carcasses [15,19,20,42]. The results presented here, however, caution against the blanket assumption that even anatomical placement of butchery marks will always be behaviorally informative. These realizations highlight the obvious but oft-violated maxim that zooarchaeological results of any profundity must proceed from well conceived and carefully articulated research questions. The current project explored the linkages propounded to exist between

intensity of prehistoric carcass processing and zooarchaeological measures, but this is just one example of problems that might be revealed with additional experimental work on this general issue.

Notes:

1 “The number of identified specimens (NISP) is a simple count of the number of observed specimens within a category of taxon and skeletal element. The MNE (minimum number of elements) is an estimate of the number of [whole] skeletal elements necessary to account for a given number of fragments” [34, p. 75; see also, 4,31].

References

- [1] Y. Abe, C.W. Marean, P.J. Nilssen, Z. Assefa, E.C. Stone, Analysis of cutmarks on archaeofauna: a review and critique of quantification procedures, and a new image-analysis GIS approach, *American Antiquity* 67 (2002) 643-663.
- [2] V. Alcántara García, R. Barba Egidio, J.M. Barral del Pino, A.B. Crespo Ruiz, A.I. Eiriz Vidal, Á. Falquina Aparicio, S. Herrero Calleja, A. Ibarra Jiménez, M. Megfas González, M. Pe´rez Gil, V. Pérez Tello, J. Rolland Calvo, J. Yravedra Sáinz de los Terreros, A. Vidal, M. Domínguez-Rodrigo, Determinación de procesos de fractura sobre huesos frescos: Un sistema de análisis de los ángulos de los planos de fracturación como discriminador de agentes bióticos, Complutum, in press.
- [3] L.R. Binford, *Nunamiut Ethnoarchaeology*, Academic Press, New York, 1978.
- [4] L.R. Binford, *Bones: Ancient Men and Modern Myths*, Academic Press, New York, 1981.
- [5] L.R. Binford, Fact and fiction about the Zinjanthropus floor: data, arguments, and interpretations, *Current Anthropology* 29 (1988) 123-149.
- [6] R.J. Blumenschine, M.M. Selvaggio, Percussion marks on bone surfaces as a new diagnostic of hominid behavior, *Nature* 333 (1988) 763-765.
- [7] R.J. Blumenschine, M.M. Selvaggio, On the marks of marrow bone processing by hammerstones and hyaenas: their anatomical patterning and archaeological implications, in: J.D. Clarke (Ed.), *Cultural Beginnings: Approaches to Understanding Early Hominid Life-ways in the African Savanna*, Dr Rudolf Habelt GMBH, Bonn, 1991, pp. 17-32.
- [8] R.J. Blumenschine, J.A. Cavallo, S.D. Capaldo, Competition for carcasses and early hominid behavioral ecology: a case study and conceptual framework, *Journal of Human Evolution* 27 (1994) 197-213.
- [9] R.J. Blumenschine, C.W. Marean, S.D. Capaldo, Blind tests of inter-analyst correspondence and accuracy in the identification of cut marks, percussion marks, and carnivore tooth marks, *Journal of Archaeological Science* 23 (1996) 493e507.
- [10] C.K. Brain, *The Hunters or the Hunted? An Introduction to African Cave Taphonomy*, University of Chicago, Chicago, 1981.
- [11] H.T. Bunn, Archaeological evidence for meat-eating by Plio-Pleistocene hominids from Koobi Fora and Olduvai Gorge, *Nature* 291 (1981) 574-577.
- [12] H.T. Bunn, Comparative analysis of modern bone assemblages from a San hunter-gatherer camp in the Kalahari Desert, Botswana, and from a spotted hyena den near Nairobi, Kenya, in: J. Clutton-Brock, C. Grigson (Eds.), *Animals and Archaeology, Hunters and Their Prey*, vol. 1, British Archaeological Reports International Series 163, London, 1983, pp. 143-148.
- [13] H.T. Bunn, Diagnosing Plio-Pleistocene hominid activity with bone fracture evidence, in: R. Bonnicksen, M.H. Sorg (Eds.), *Bone Modification*, Center for the Study of the First Americans, Orono (ME), 1989, pp. 299-315.
- [14] H.T. Bunn, Early Pleistocene hominid foraging strategies along the ancestral Omo River at Koobi Fora, Kenya, *Journal of Human Evolution* 27 (1994) 247-266.
- [15] H.T. Bunn, Hunting, power scavenging, and butchering by Hadza foragers and by Plio-Pleistocene Homo, in: C.B. Stanford, H.T. Bunn (Eds.), *Meat-eating and Human Evolution*, Oxford University Press, New York, 2001, pp. 199-218.
- [16] H.T. Bunn, J.A. Ezzo, Hunting and scavenging by Plio-Pleistocene hominids: nutritional constraints, archaeological patterns, and behavioural implications, *Journal of Archaeological Science* 20 (1993) 365-398.
- [17] O. Burger, M.J. Hamilton, R. Walker, The prey as patch model: optimal handling of resources with diminishing returns, *Journal of Archaeological Science* 32 (2005) 1147-1158.

- [18] S.D. Capaldo, R.J. Blumenshine, A quantitative diagnosis of notches made by hammerstone percussion and carnivore gnawing in bovid long bones, *American Antiquity* 59 (1994) 724-748.
- [19] M. Domínguez-Rodrigo, Hunting and scavenging in early hominids: the state of the debate, *Journal of World Prehistory* 16 (2002) 1-56.
- [20] M. Domínguez-Rodrigo, T.R. Pickering, Early hominid hunting and scavenging: a zooarchaeological review, *Evolutionary Anthropology* 12 (2003) 275-282.
- [21] M. Domínguez-Rodrigo, T.R. Pickering, S. Semaw, M. Rogers, Cut-marked bones from Pliocene archaeological sites at Gona, Afar, Ethiopia: implications for the function of the world's oldest stone tools, *Journal of Human Evolution* 48 (2005) 109-121.
- [22] C.P. Egeland, Carcass processing intensity and cutmark creation: an experimental approach, *Plains Anthropologist* 48 (2003) 39-51.
- [23] C.P. Egeland, R.M. Byerly, Application of return rates to large mammal butchery and transport among hunter-gatherers and its implications for Plio-Pleistocene hominid carcass foraging and site use, *Journal of Taphonomy* 3 (2005) 135-158.
- [24] J.W. Fisher, Bone surface modifications in zooarchaeology, *Journal of Archaeological Method and Theory* 2 (1995) 7-68.
- [25] R.A. Gould, Faunal reduction at Puntutjarpa Rockshelter, Warburton Ranges, Western Australia, *Archaeology of Oceania* 31 (1996) 72-86.
- [26] D.K. Grayson, F. Delpech, Ungulates and the Middle-to-Upper Paleolithic transition at Grotte XVI (Dordogne, France), *Journal of Archaeological Science* 30 (2003) 1633-1648.
- [27] H.J. Greenfield, The origins of metallurgy: distinguishing stone from metal cut-marks on bones from archaeological sites, *Journal of Archaeological Science* 26 (1999) 797-808.
- [28] J. de Heinzelin, J.D. Clark, T. White, W. Hart, P. Renne, G. Wold-Gabriel, Y. Beyene, E. Vrba, Environment and behavior of 2.5-million-year-old Bouri hominids, *Science* 284 (1999) 625-629.
- [29] R.L. Lyman, Archaeofaunas and butchery studies: a taphonomic perspective, *Advances in Archaeological Method and Theory* 10 (1987) 249-337.
- [30] R.L. Lyman, Prehistoric seal and sea-lion butchering on the southern Northwest Coast, *American Antiquity* 57 (1992) 246e261.
- [31] R.L. Lyman, *Vertebrate Taphonomy*, Cambridge University, Cambridge, 1994.
- [32] R.L. Lyman, A study of variation in the prehistoric butchery of large artiodactyls, in: E. Johnson (Ed.), *Ancient Peoples and Landscapes*, Museum of Texas Tech University, Lubbock, 1995, pp. 233-253.
- [33] R.L. Lyman, Analyzing cutmarks: lessons from artiodactyl remains in the northwestern United States, *Journal of Archaeological Science* 32 (2005) 1722-1732.
- [34] C.W. Marean, M. Domínguez-Rodrigo, T.R. Pickering, Skeletal element equifinality in zooarchaeology begins with method: the evolution of the "shaft critique", *Journal of Taphonomy* 2 (2004) 69-98.
- [35] T.H. McGovern, T. Amorosi, S. Perdikaris, J. Woollet, Vertebrate zooarchaeology of Sandnes V51: economic change at a chieftain's farm in West Greenland, *Arctic Anthropology* 33 (1996) 94-121.
- [36] R.G. Milo, Evidence for human predation at Klasies River Mouth, South Africa, and its implications for the behaviour of early modern humans, *Journal of Archaeological Science* 25 (1998) 99-133.
- [37] N.D. Munro, Zooarchaeological measures of hunting pressure and occupation intensity in the Natufian: implications for agricultural origins, *Current Anthropology* 45 (2004) S5-S33.
- [38] N.D. Munro, G. Bar-Oz, Gazelle bone fat processing in the Levantine Epipalaeolithic, *Journal of Archaeological Science* 32 (2005) 223-239.
- [39] A.K. Outram, A comparison of Paleo-Eskimo and Medieval Norse bone fat exploitation in western Greenland, *Arctic Anthropology* 36 (1999) 103-117.
- [40] A.K. Outram, A new approach to identifying bone marrow and grease exploitation: why the "indeterminant" fragments should not be ignored, *Journal of Archaeological Science* 28 (2001) 401-410.
- [41] P.W. Parmalee, The food economy of Archaic and Woodland peoples at the Tick Creek Cave Site, Missouri, *The Missouri Archaeologist* 27 (1965) 1-34.
- [42] T.R. Pickering, M. Domínguez-Rodrigo, The acquisition and use of large mammal carcasses by Oldowan hominins in Eastern and Southern Africa: a selected review and assessment, in: N. Toth, K. Schick

(Eds.), *The Oldowan: Studies into the Origins of Human Technology*, Stone Age Institute Press, Bloomington (IN), in press.

[43] T.R. Pickering, C.W. Marean, M. Domínguez-Rodrigo, Importance of limb bone shafts in zooarchaeology: a response to “On in situ attrition and vertebrate body part profiles” (2002), by M.C. Stiner, *Journal of Archaeological Science* 30 (2003) 1469-1482.

[44] T.R. Pickering, M. Domínguez-Rodrigo, C.P. Egeland, C.K. Brain, New data and ideas on the foraging behaviour of Early Stone Age hominids at Swartkrans Cave, South Africa, *South African Journal of Science* 100 (2004) 215-219.

[45] T.R. Pickering, M. Domínguez-Rodrigo, C.P. Egeland, C.K. Brain, Beyond leopards: tooth marks and the relative contribution of multiple carnivore taxa to the accumulation of the Swartkrans Member 3 fossil assemblage, *Journal of Human Evolution* 46 (2004) 595-604.

[46] T.R. Pickering, M. Domínguez-Rodrigo, C.P. Egeland, C.K. Brain, The contribution of limb bone fracture patterns to reconstructing early hominid behavior at Swartkrans Cave (South Africa): archaeological application of a new analytical method, *International Journal of Osteoarchaeology* 15 (2005) 247-260.

[47] T.R. Pickering, M. Domínguez-Rodrigo, C.P. Egeland, C.K. Brain, Carcass foraging by early hominids at Swartkrans Cave (South Africa): a new investigation of the zooarchaeology and taphonomy of Member 3, in: T.R. Pickering, K. Schick, N. Toth (Eds.), *African Taphonomy: A Tribute to the Career of C.K. “Bob” Brain*, Stone Age Institute Press, Bloomington (IN), in press.

[48] T.R. Pickering, M. Domínguez-Rodrigo, C.P. Egeland, C.K. Brain, The earliest evidence of hominid butchery in southern Africa: new zooarchaeological and taphonomic data on the use of large animal carcasses at Swartkrans Members 1e3. Paper presented at the XIVth Annual Meeting of the Paleoanthropology Society, held in Milwaukee, Wisconsin, April 4-6, 2005.

[49] L.C. Todd, D.J. Rapson, Long bone fragmentation and interpretation of faunal assemblages: approaches to comparative analysis, *Journal of Archaeological Science* 15 (1988) 307-325.

[50] C.G. Turner, Taphonomic reconstruction of human violence and cannibalism based on mass burials in the American Southwest, in: G.M. LeMoine, A.S. MacEachern (Eds.), *Carnivores, Human Scavengers and Predators: A Question of Bone Technology*, University of Calgary Archaeological Association, Calgary, 1983, pp. 219-240.

[51] P. Villa, E. Mahieu, Breakage patterns of human long bones, *Journal of Human Evolution* 21 (1991) 27-48.

[52] P.L. Walker, J.C. Long, An experimental study of the morphological characteristics of tool marks, *American Antiquity* 42 (1977) 605-616.

[53] T.D. White, *Prehistoric Cannibalism at Mancos 5MTUMR-2346*, Princeton University Press, Princeton, 1992.