quaternary

MDPI

Article

Macroscopic Chop Mark Identification on Archaeological Bone: An Experimental Study of Chipped Stone, Ground Stone, Copper, and Bronze Axe Heads on Bone

Tiffany R. Okaluk * and Haskel J. Greenfield

Department of Anthropology, St. Paul's College, University of Manitoba, 70 Dysart Road,
Winnipeg, MB R3T 2M6, Canada; haskel.greenfield@umanitoba.ca
* Correspondence: tiffanyokaluk@gmail.com

Abstract: This paper presents a new macroscopic method for identifying chop marks on archaeological faunal assemblages and highlights the major differences in the morphology of chop marks created by stone and metal axes. The method provides macroscopic criteria that aid in the identification of both complete and incomplete chop mark types as well as the raw material of the axe. Experiments with modern stone (chipped and ground) and metal (copper and bronze) axes found that the degree of fragmentation within a chop mark is related to both the width and sharpness of the axe and can be classed on a scale from 1–5 using a variety of criteria. The experiments demonstrate that sharp chipped stone axes are fragile (often break upon impact) and do not create clean and well-defined chop marks. Ground stone axes are more durable but tend to create very fragmented chop marks without a clean cut (sheared) surface. Unalloyed copper metal axes can create sheared chopped surfaces; however, the relatively soft metal creates more crushing at the point of entry than bronze axes. In contrast, bronze axes are durable and create chop marks with exceptionally low rates of fragmentation resulting in a clean-cut sheared surface that extends into the bone for more than 3 mm. The method is applied to the faunal assemblage from the Early Bronze Age site of Göltepe, Turkey to determine whether the chop marks on bones were made by stone or metal axes at this early metal processing settlement. The results suggest that many of the chop marks were made by metal implements (e.g., axes). Hence, this method provides another means to monitor the adoption rates of new raw materials at a time when both metal and stone axes coexisted.

Keywords: butchery; chopping tools; axe marks; chop marks; experimental archaeology; ground stone tools; chipped stone tools; copper tools; bronze tools; Early Bronze Age; Anatolia; Near East; innovation; origins of metallurgy

check for updates

Citation: Okaluk, T.R.; Greenfield, H.J. Macroscopic Chop Mark Identification on Archaeological Bone: An Experimental Study of Chipped Stone, Ground Stone, Copper, and Bronze Axe Heads on Bone. *Quaternary* **2022**, *5*, 15. https://doi.org/10.3390/quat5010015

Academic Editors: Juan Rofes, Janine Ochoa and Emmanuelle Stoetzel

Received: 21 July 2021
Accepted: 4 January 2022
Published: 2 March 2022

1. Introduction

Animal carcass butchery practices involve a variety of tools, and the resulting actions include bashes, chops, saw marks, and slices. The resulting marks on bone allow zooarchaeologists to map out the process by which the carcass is prepared from slaughter, to secondary stages (skinning, dismemberment, and disarticulation), and final stages (marrow extraction, and filleting) [1–4]. Each of these actions leaves diagnostic marks on the bones. The location and types of marks can also inform on butchering tool preference and raw material choices [5–7], as well as cultural preferences related to food preparation [8–11].

A growing literature exists to define, differentiate, and contextualise slice marks found on archaeological animal bone, e.g., [5,12–20]. Methods for the analysis of slice marks benefit from over 40 years of dedicated experimental, methodological, and theoretical work. Recently, the use of 3D modelling, micro-photogrammetry, and deep learning algorithms has begun to revolutionise the accuracy by which zooarchaeologists recognise and differentiate cut marks by creating more objectivity [18,21–24].

Chop marks, however, have received far less attention and the methods of description and identification are not as advanced on archaeological bone [25,26]. Minimal research has been conducted on chop mark distinguishing characteristics on archaeological bone to identify the raw material choice for the axe and the nature of tool production [20]. Although chop mark studies are not new in the world of zooarchaeology, they are in their infancy when compared to slice marks.

Chopping is an essential part of the butchering process, particularly with respect to dismemberment and disarticulation of limbs and carcasses into portions and for marrow extraction. Bones have been chopped since the Lower Palaeolithic [27–29], and chopping continues to be an important part of carcass preparation in historical [3,30] and modern eras [31]. However, chop marks are not always easy to identify as some are difficult to differentiate from natural breakage, do not leave an easily identifiable chop mark, leave only one side or only a partial mark, or are masked by breakage resulting from marrow processing [32–34]. These types of bone breakage inhibit the identification of chop marks and analysis of this type of butchery mark in detail and our ability to monitor the transition from a stone- to metal-based chopping technology.

In contrast to slice marks, the diagnostic criteria for what constitutes chop marks are not well-defined other than being a somewhat V-shaped impact mark with impact fractures and/or splinters [20,35,36]. However, it is often not possible to apply such criteria if the chop is successful and completely severs the bone. Chopping action on bone creates an incredibly varied range of marks that take multiple macroscopic forms (complete, incomplete, breakage, and shearing). Similar identification problems exists if the tool is roughly formed and/or does not have a sharp and smooth V-shaped edge. This is particularly true with respect to Palaeolithic chipped stone tools, with their differentially shaped ventral and dorsal sides. The lack of specific identification criteria based on experimental studies creates a reciprocal cycle where chop marks are understudied as a line of evidence for butchery practices and tool use.

This lacuna in the study of chop marks is particularly important in the periods when the types of chopping instruments and styles of butchery dramatically evolve over time, particularly with the introduction of new raw materials for axes such as copper, bronze, and iron—in other words, in the Chalcolithic, Bronze, and Iron Ages. While stone tools preserve well, metal tools do not. When they break or are otherwise damaged, they can be melted down and made anew. Consequently, they are much rarer in the archaeological record and cannot be quantitatively used to identify when the transition from a stone to a metal-based chopping technology occurred [7,16].

The existing assemblage of metal items from even later prehistoric and historic sites is only a relatively small percentage of what was originally produced and circulated. Therefore, the higher frequency of chop marks on bones can become a proxy measure for the frequency of tools that have not preserved, and it becomes possible to monitor changes in the frequency of raw material choice, tool form, and tool production over time.

In this paper, we present our recent experimental research to aid in the definition of macroscopic diagnostic differences between several types of chopping tool shapes and raw material choices. Our study demonstrates that the macroscopic morphology of chop marks generally reflects the raw material of the chopping tool (metal versus stone), as well as the nature of tool production (ground versus chipped stone). The experiments focus on chipped stone, ground stone, copper, and bronze axes as these were the tool types available during the transition from a stone to bronze chopping technology during our periods of interest—the Late Chalcolithic (LC) and Early Bronze Age (EBA) of Anatolia [35–37].

This analysis is part of our long-term effort to identify the nature of butchering tools in zooarchaeological assemblages during this crucial period when bronze metallurgy appeared [7,9–11,16,38–47]. Our experimental results are used to differentiate and identify the type of chopping instruments used at the site of Göltepe from central Turkey, at the dawn of the Bronze Age. This experimental study aims to identify and understand the *macroscopic* differences between chop marks made by different types of metal and stone axes potentially used at the site during this crucial period in the evolution of metallurgical technologies.

2. Butchery Chopping Experimental Studies—A Brief Review

2.1. Archaeological Chop Mark Experimentation

Chops are created by sharp wedge-shaped tools that strike the bone with force and are designed to bite into or sever the bone. The limited archaeological literature on chop marks often defines these marks as wide U/V-shaped marks ([2,20], [48] (p. 349), [49]). Alternatively, and more recently, chop marks are sometimes described as a flat/planar surface created by an axe [50]. Further, an experimental study suggests that chop marks made by stone and metal axes have different morphological traits and can be differentiated based on those traits—stone axes left wide U-shaped marks on bone, whereas metal axes left deep V-shaped marks on bone [48].

While pointing the way, these very general criteria do not address chop marks that completely sever the bone. The action of chopping is intended to divide the bone into separate pieces. If the action of chopping results in the division of the bone into multiple pieces, then deep U or V shapes are an unintended consequence of a failed or incomplete chop. Both complete (full separation of the bone) and incomplete (incomplete separation of the bone) chop marks are examined in this study.

2.2. Forensic Chop Mark Experimentation

Forensic and human skeletal researchers have long conducted experiments to identify the effects on bone fragmentation as a function of the type, size, and shape of metal chopping instruments [25,26,51–55]. For the most part, their focus is on the type of metal chopping tool used in potential modern murders. It is clear from these experiments that both the width and sharpness of a metal chopping (axe) or hacking (with a sword/machete) instrument affects how the bone fractures upon impact. A wide and dull metal instrument is more likely to shatter the bone on impact, whereas a thin sharp instrument (sword/machete) is more likely to cut through a significant portion of the bone before fragmentation occurs [56].

A common observation between all such experimental chopping studies is bone fragmentation. High-speed impact from an axe will often result (up to 30% of the time) in complete fragmentation of the bone and can leave very little evidence on the bone material of the chopping event [52]. Even when complete fragmentation does not occur, a clean cut through the bone may only be visible anywhere from a few mm to a few cm into the surface of the bone before the bone fragments/splits due to the force of the tool and stress on the bone due to wedge action. The degree of wedge action is directly related to the width of the tool. Therefore, a thinner metal blade can cut into the bone much deeper than a wide tool.

The problem with directly extrapolating these conclusions from experimental forensic studies for use in archaeological identification is that these studies focus exclusively on modern steel metal tools. It is unknown if the same diagnostic criteria apply to early copper and bronze axes, and how chop marks made by various types of stone axes (chipped and ground) compare to both ancient and modern metal axes. As tool shape, material, and sharpness are all intrinsically related to the morphology of the mark left behind on the bone, it is imperative that all chopping tool types be systematically tested.

3. Materials and Methods

Five replica axes were made and tested in a series of seven separate chopping tests carried out on wood, *Ovis aries* (sheep) crania, *Bos taurus* (cattle) and *Sus scrofa* (pig) ribs, *Sus scrofa* vertebra, and *Odocoileus virginianus* (deer) and *Sus scrofa* long bones. All chops were made by a single individual to control for the relative skill, force, and technique in the butchery process. Each axe was used on a separate bone specimen in every test. The goal of each test was to separate/divide the bone to simulate dismemberment activity. This often-required multiple strikes and was not successful in every test.

3.1. Replica Axe Materials

The five replica axe heads were made from five different types of raw materials: (1) bronze (10% tin: 90% copper), (2) cold hammered pure copper, (3) ground stone (fine basalt), (4) chipped stone (fine grained chert), and (5) chipped stone (Knife River Flint) (Figure 1). The raw materials for the axe heads were selected to represent the range of raw materials used to make axes in LC and EBA Anatolia and also according to what was locally available and feasible within modern contexts for the experiments. Even though arsenical copper is found on the Anatolian plateau during the EBA, it was not included in the experiment since the resulting axe would be as hard and morphologically similar to a tin-bronze axe [57].

Figure 1. (**a**) The five experimental axes (left to right): bronze, copper, ground stone, chert chipped stone, and Knife River Flint chipped stone; and (**b**) close-up of the same axe heads in the same order as above.

Flint and chert are the raw materials selected for the chipped stone axe heads as these are the most common materials used for these types of axe heads [36,58] (Figure 1). The shape of the chipped and ground stone experimental axes are similar in shape to those found during the LC and EBA. Two sizes and shapes of chipped stone (flint and chert) axe heads are used in the experiment. The chert axe head is robust, and the flint is quite fine and very sharp. Both are bifacially worked, but neither bit is ground down to strengthen the edge since they are modern replicas on loan. The ground stone axes from this region are quite thick [35] with a steep pitch leading to the sharpened edge (Figure 2). The replica is shaped with this in mind. The ground stone axe is made from a fine grain basalt and shaped on a grinding wheel. For detailed description of experimental axe replicas and how they were hafted, see Table 1.

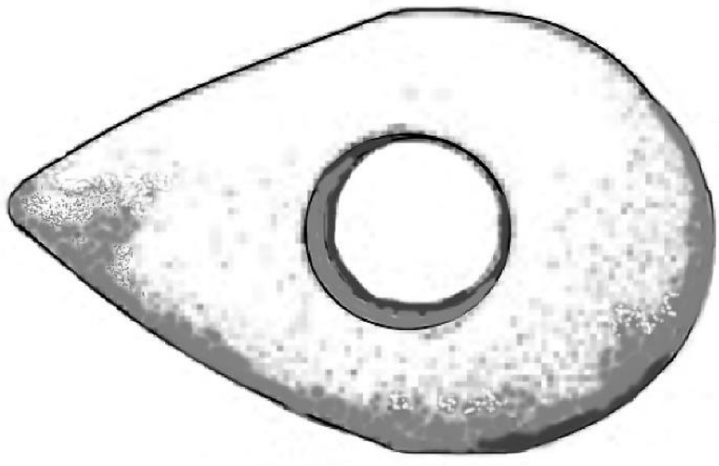

Figure 2. EBII Ground stone axe recovered from Demircihöyük–Sarıket cemetery. Image reproduced from Massa (2014) with permission from Cambridge University Press.

Table 1. Construction materials and techniques used for the experimental axes.

	Bronze	**Copper**	**Ground Stone**	**Chipped Stone (A)**	**Chipped Stone (B)**
Axe head raw material	90% copper; 10% tin	100% copper (cold hammered)	Fine gained basalt	Fine grained chert	Knife River Flint
Handle raw material	Cherry	Pine	Cherry	Pine	Pine
Haft	Pine resin, sinew, leather cord	Pine resin, sinew, leather cord	Epoxy	Sinew, leather cord	Sinew, leather cord

Although obsidian was available in Anatolia and used for slicing blades, non-votive obsidian axes in the LC and EBA are virtually unheard of. No evidence for the sustained use of obsidian axes is known from the archaeological record in Anatolia or the Levant. Only small ad hoc obsidian flakes were found at Göltepe, and there is no evidence for larger chipped stone tools regardless of the type of stone [59]. Obsidian is a fragile material and is prone to breakage.

Kononenko et al. [60] used a series of 11 experimental obsidian axes to see if the axes could withstand pressures from woodworking. Although the axes could chop through the soft wood, the axes suffered considerable damage. The tools were only useful for between 20 min–1 h before they broke completely and were discarded. The authors of the experimental study concluded that obsidian was only capable of chopping soft wood and is not suitable for harder materials. The materials used for stone axes in Anatolia and the southern Levant are flint and basalt, and these are the materials we chose for use in our study.

3.2. *Experimental Bone Sample*

Each axe type was tested on several domestic (cattle, sheep, and pig) and wild taxa (white-tailed deer), and osteological elements commonly found in archaeological assemblages (long bones/radius, ulna, tibia, flat bones/rib, irregular bones/cranium and vertebra, etc.). The goal of including multiple element types and animal size classes is to test the chopping capabilities of the different axe types and control for some of the potential variation due to differential bone density (Table 2).

Table 2. Bone sample characteristics.

Bone Sample (Taxon and Element)	Age	Size Class	Amount of Meat (mm) Covering the Bone
Ovis aries crania	Juvenile	Medium	2–5 mm
Bos taurus ribs	Young adult	Large	5 mm
Sus scrofa ribs	Sub-adult	Large	10 mm
Sus scrofa long bones	Sub-adult	Large	20 mm
Sus scrofa vertebrae	Sub-adult	Large	20–25 mm
Odocoileus virginianus long bones	Juvenile	Medium	2–10 mm

All specimens are from older juvenile, sub-adult, and young adult individuals and were purchased from local supermarkets. Only the ossified bone segments were dense enough to survive chopping and leave any diagnostic marks on the bones. Chop marks intersecting unossified bone often separated along ossification/fusion lines during maceration and created problems in identifying and quantifying these chop marks. As a result, these chop marks were not recorded and were discarded from the overall sample resulting in different numbers of chop marks from each axe type as the exact age of the animal was unknown before processing.

In general, meat and skin were not removed prior to chopping to better simulate the dismemberment process. Each bone specimen had at least 2–5 mm (or more) of meat covering the surface of the bone when chopped. The chipped stone axes had difficulty penetrating the bone and sometimes even struggled to cut through the soft flesh. This resulted in significantly fewer chop marks created by the chipped stone axes.

Each axe type was initially tested on a one-inch-thick flat plank of soft wood (pine). Flat pine wood boards provide a relatively even (flat), soft (as to not damage the axe edge), consistent internal structure (avoids the problem of differential bone density). Elsewhere, it has been successfully employed as a control medium for butchering experiments [16]. Second, each axe type was tested on the different bone types from the various taxa. The specifics of each test are described below. Each chopping test was conducted only by the senior author (right-handed, adult female) to control for differential abilities and strength across all tests.

Chops were directed into the bone at both c. 90° and 45° angles to attempt to mimic the angle at which chops are often observed in the archaeological record. It was found that the chop marks were more successful in penetrating the bone surface when directed at a 45° angle.

All axes were tested in both sharp and dull states, and any deformation of the axe bits due to damage was noted before and after each test.

Each chopped bone specimen was boiled (2–3 h), de-fleshed by hand so as not to introduce any unintended tool marks, and re-boiled (2–3 h) to loosen any remaining muscle tissue and extract as much grease as possible. Subsequently, the specimen was left to dry out slowly, and was then labelled, photographed, and the resulting marks were described.

The specimens used in the experiments and from the archaeological site of Göltepe are both curated in the Near Eastern and Biblical Archaeology Lab of St. Paul's College of the University of Manitoba and are available for verification.

3.3. Recording and Attributes of Investigation

All chop marks were given a specimen and chop number. Basic zooarchaeological information was recorded for each specimen, including the species, element, location of the mark, and age of the animal. The variables under investigation within this study were: (1) whether the chop was complete or incomplete; (2) the degree of fragmentation within the chop mark on a scale from 1–5, (3) the depth of chop mark into the surface of the bone, (4) the degree of crushing at the location of impact, (5) the angle of chop, (6) the sharpness of the axe, and (7) whether the breakage was smooth due to cutting or irregular (e.g., jagged) due to uneven breakage or crushing. These data are summarised in Table 3.

Table 3. Summary of data for all experimental axe chop marks (cBI—*chopped Butchering Incident*).

cBI	Species	Element	Axe Raw Material	Complete/ Incomplete	Angle of Chop	Sheared/ Not Sheared	Fragmentation Class	Degree of Crushing	Sharp/Dull
1	*Sus scrofa*	Radius	Bronze	Complete	90°	Sheared	5	None	Dull
2	*Sus scrofa*	Radius	Bronze	Complete	90°	Not sheared	3	Light	Dull
3	*Sus scrofa*	Radius	Bronze	Incomplete	90°	Surface	Surface	None	Dull
4	*Sus scrofa*	Radius	Bronze	Complete	45°	Sheared	4	None	Dull
5	*Sus scrofa*	Sternum	Bronze	Complete	45°	Sheared	5	None	Dull
6	*Sus scrofa*	Sternum	Bronze	Complete	45°	Sheared	4	None	Dull
7	*Sus scrofa*	Rib	Bronze	Complete	90°	Not sheared	3	None	Sharp
8	*Sus scrofa*	Rib	Bronze	Complete	90°	Not sheared	2	None	Sharp
9	*Sus scrofa*	Rib	Bronze	Incomplete	45°	Sheared	4	Light	Sharp
10	*Sus scrofa*	Rib	Bronze	Incomplete	90°	Not sheared	3	None	Sharp
11	*Sus scrofa*	Rib	Bronze	Complete	90°	Sheared	5	None	Sharp
12	*Sus scrofa*	Rib	Bronze	Complete	90°	Not sheared	3		Sharp
13	*Sus scrofa*	Rib	Bronze	Complete	90°	Not sheared	3	None	Sharp
14	*Sus scrofa*	Rib	Bronze	Complete	45°	Sheared	5	Light	Sharp
15	*Sus scrofa*	Rib	Bronze	Complete	90°	Sheared	5	None	Sharp
16	*Sus scrofa*	Rib	Bronze	Complete	45°	Sheared	4	Medium	Sharp
17	*Sus scrofa*	Rib	Bronze	Complete	90°	Not sheared	2	Light	Sharp
18	*Sus scrofa*	Rib	Bronze	Complete	45°	Sheared	5	None	Sharp
19	*Sus scrofa*	Rib	Bronze	Incomplete	90°	Surface	Surface	None	Sharp
52	*Bos taurus*	Rib	Bronze	Incomplete	45°	Sheared	5	None	Sharp
21	*Bos taurus*	Rib	Bronze	Incomplete	90°	Not sheared	3	Light	Dull
22	*Bos taurus*	Rib	Bronze	Incomplete	90°	Surface	Surface	No	Dull
23	*Bos taurus*	Rib	Bronze	Incomplete	90°	Surface	Surface	No	Dull
24	*Odocoileus virginiaus*	Tibia	Bronze	Incomplete	45°	Sheared	4	Light	Sharp
25	*Odocoileus virginiaus*	Tibia	Bronze	Complete	90°	Not sheared	3	None	Sharp
26	*Odocoileus virginiaus*	Humerus	Bronze	Complete	45°	Sheared	5	None	Sharp
27	*Odocoileus virginiaus*	Humerus	Bronze	Incomplete	90°	Surface	Surface	None	Sharp
28	*Ovis aries*	Cranium	Bronze	Incomplete	90°	Not sheared	3	None	Dull
29	*Ovis aries*	Cranium	Bronze	Complete	90°	Sheared	4	Medium	Dull
30	*Ovis aries*	Cranium	Bronze	Complete	90°	Not sheared	3	Medium	Dull
31	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	3	Light	Sharp
32	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	3	Light	Sharp
33	*Sus scrofa*	Rib	Copper	Incomplete	45°	Sheared	4	Light	Sharp
34	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	3	None	Sharp
35	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	2	Light	Sharp
36	*Sus scrofa*	Rib	Copper	Incomplete	90°	Surface	Surface	Light	Sharp
37	*Sus scrofa*	Rib	Copper	Incomplete	45°	Surface	Surface	None	Sharp
38	*Sus scrofa*	Rib	Copper	Complete	90°	Sheared	4	None	Sharp
39	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	3	Light	Sharp
40	*Sus scrofa*	Rib	Copper	Incomplete	90°	Surface	Surface	None	Sharp
41	*Sus scrofa*	Rib	Copper	Complete	45°	Sheared	4	None	Sharp
42	*Sus scrofa*	Rib	Copper	Complete	45°	Not sheared	2	None	Sharp
43	*Sus scrofa*	Rib	Copper	Incomplete	45°	Surface	Surface	None	Sharp
44	*Sus scrofa*	Rib	Copper	Complete	45°	Sheared	5	None	Sharp
45	*Sus scrofa*	Rib	Copper	Complete	45°	Sheared	4	None	Sharp
46	*Sus scrofa*	Rib	Copper	Complete	45°	Not sheared	3	Light	Sharp
47	*Sus scrofa*	Rib	Copper	Complete	45°	Not sheared	2	None	Sharp
48	*Sus scrofa*	Rib	Copper	Complete	45°	Not sheared	3	None	Sharp
49	*Sus scrofa*	Ulna/radius	Copper	Incomplete	45°	Surface	Surface	None	Dull
50	*Bos taurus*	Rib	Copper	Incomplete	90°	Surface	Surface	Medium	Dull
51	*Bos taurus*	Rib	Copper	Incomplete	45°	Surface	Surface	Heavy	Dull
25	*Bos taurus*	Rib	Copper	Incomplete	90°	Surface	Surface	Heavy	Dull
53	*Bos taurus*	Rib	Copper	Incomplete	90°	Surface	Surface	Heavy	Dull
54	*Odocoileus virginianus*	Tibia	Copper	Complete	45°	Not sheared	1	Medium	Sharp
55	*Odocoileus virginianus*	Tibia	Copper	Complete	45°	Not sheared	1	Light	Sharp
56	*Odocoileus virginianus*	Tibia	Copper	Incomplete	45°	Not sheared	3	Medium	Sharp
57	*Ovis aries*	Cranium	Copper	Incomplete	45°	Sheared	4	None	Sharp
58	*Ovis aries*	Cranium	Copper	Incomplete	45°	Sheared	4	Light	Dull
59	*Sus scrofa*	Vertebra	Copper	Complete	90°	Not sheared	2	Light	Dull

Table 3. *Cont.*

cBI	Species	Element	Axe Raw Material	Complete/ Incomplete	Angle of Chop	Sheared/ Not Sheared	Fragmentation Class	Degree of Crushing	Sharp/Dull
60	*Sus scrofa*	Vertebra	Copper	Complete	90°	Not sheared	3	Light	Dull
61	*Sus scrofa*	Rib	Copper	Incomplete	90°	Not sheared	2	None	Sharp
62	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	2	Light	Sharp
63	*Sus scrofa*	Rib	Copper	Complete	90°	Not sheared	1	Light	Sharp
64	*Sus scrofa*	Rib	Copper	Complete	45°	Not sheared	1	None	Sharp
65	*Sus scrofa*	Vertebra	Copper	Complete	90°	Not sheared	3	Light	Sharp
66	*Sus scrofa*	Vertebra	Copper	Complete	45°	Sheared	4	None	Sharp
67	*Sus scrofa*	Vertebra	Copper	Complete	45°	Not sheared	3	Light	Sharp
68	*Sus scrofa*	Vertebra	Copper	Complete	90°	Sheared	5	Light	Sharp
69	*Sus scrofa*	Vertebra	Copper	Complete	45°	Sheared	4	Light	Sharp
70	*Sus scrofa*	Vertebra	Copper	Complete	45°	Sheared	4	None	Sharp
71	*Ovis aries*	Cranium	Copper	Incomplete	45°	Not sheared	3	None	Dull
72	*Bos taurus*	Rib	Ground stone	Incomplete	90°	Not sheared	2	Heavy	Sharp
73	*Bos taurus*	Rib	Ground stone	Incomplete	90°	Not sheared	1	Heavy	Sharp
74	*Bos taurus*	Rib	Ground stone	Incomplete	90°	Not sheared	1	Heavy	Sharp
75	*Bos taurus*	Rib	Ground stone	Incomplete	90°	Not sheared	1	Medium	Sharp
76	*Bos taurus*	Rib	Ground stone	Incomplete	90°	Surface	Surface	None	Sharp
77	*Sus scrofa*	Vertebra	Ground stone	Complete	45°	Not sheared	3	Medium	Sharp
78	*Sus scrofa*	Vertebra	Ground stone	Complete	45°	Not sheared	3	Light	Sharp
79	*Odocoileus virginianus*	Radius	Ground stone	Complete	90°	Not sheared	2	Medium	Dull
80	*Odocoileus virginianus*	Radius	Ground stone	Incomplete	90°	Surface	Surface	None	Dull
81	*Odocoileus virginianus*	Radius	Ground stone	Incomplete	90°	Surface	Surface	Light	Dull
82	*Sus scrofa*	Vertebra	Ground stone	Complete	45°	Not sheared	2	None	Sharp
83	*Sus scrofa*	Vertebra	Ground stone	Complete	45°	Not sheared	3	Light	Sharp
84	*Ovis aries*	Cranium	Ground stone	Incomplete	90°	Surface	Surface	Light	Sharp
85	*Ovis aries*	Cranium	Ground stone	Incomplete	45°	Not sheared	3	Light	Sharp
86	*Ovis aries*	Cranium	Ground stone	Complete	90°	Not sheared	3	Light	Sharp
87	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	2	Light	Dull
88	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	2	Light	Dull
89	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Light	Dull
90	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Light	Dull
91	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Heavy	Dull

Table 3. *Cont.*

cBI	Species	Element	Axe Raw Material	Complete/ Incomplete	Angle of Chop	Sheared/ Not Sheared	Fragmentation Class	Degree of Crushing	Sharp/Dull
92	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Light	Dull
93	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Medium	Dull
94	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Medium	Dull
95	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	2	Heavy	Dull
96	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Heavy	Dull
97	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	2	Light	Dull
98	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Light	Dull
99	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	3	None	Dull
100	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	3	None	Dull
101	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	2	Light	Dull
102	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	1	Light	Dull
103	*Sus scrofa*	Rib	Ground stone	Incomplete	90°	Surface	Surface	None	Dull
104	*Sus scrofa*	Rib	Ground stone	Complete	45°	Not sheared	3	None	Dull
105	*Odocoileus virginianus*	Radius	Chipped stone	Complete	90°	Not sheared	1	Light	Dull
106	*Odocoileus virginianus*	Radius	Chipped stone	Incomplete	90°	Surface	Surface	None	Dull
107	*Odocoileus virginianus*	Radius	Chipped stone	Incomplete	90°	Surface	Surface	Light	Dull
108	*Bos taurus*	Rib	Chipped stone	Incomplete	90°	Not sheared	Surface	None	Sharp
109	*Bos taurus*	Rib	Chipped stone	Incomplete	90°	Not sheared	Surface	None	Sharp
110	*Bos taurus*	Rib	Chipped stone	Incomplete	90°	Not sheared	Surface	None	Sharp
111	*Ovis aries*	Cranium	Chipped stone	Incomplete	90°	Not sheared	3	Medium	Sharp
112	*Ovis aries*	Cranium	Chipped stone	Complete	90°	Not sheared	1	Light	Sharp
113	*Ovis aries*	Cranium	Chipped stone	Complete	45°	Not sheared	2	Medium	Sharp
114		Cranium	Chipped stone	Complete	90°	Not sheared	1	Heavy	Sharp
115	*Ovis aries*	Cranium	Chipped stone	Incomplete	90°	Surface	Surface	Medium	Sharp
116	*Ovis aries*	Cranium	Chipped stone	Complete	45°	Not sheared	2	Light	Sharp
117	*Ovis aries*	Cranium	Chipped stone	Complete	90°	Not sheared	1	Light	Sharp

3.4. Scale of Observation

The data presented are based on macroscopic observations. This scale of analysis was chosen for this experiment for three reasons: (1) Chop mark diagnostics are often large enough to be seen by the naked eye [51]. (2) Macroscopic chop mark diagnostic criteria can be defined to distinguish different kinds of axe shapes, production types, and general raw material type. This allows even field-based analysts without access to advanced instrumentation to collect data. (3) Raw material type identifications using microscopic techniques (e.g., SEM, 3D modelling, and micro-photogrammetry) depend on the creation of a surface where the tool imprints a recognisable mark on the bone.

It is only when there is sufficient direct contact between the bone and the tool where a unique identifying signature is created and the material type can be identified [26]. Unfortunately, chop marks do not always produce such a surface since the tool does not always cut cleanly into the bone so as to produce a diagnostic surface. Surfaces are often crushed, chops are incomplete, or the bone completely fragments upon impact. Therefore, traditional methods of microscopic analysis that hinge on viewing the entire area of contact between the bone and tool are not appropriate for analysing all chop marks within an assemblage. Microscopic analysis is only appropriate for chop marks that exhibit a cut/sheared surface [26]. As will be demonstrated below, EBA stone axes are unlikely to create cut/sheared surfaces on bone, while metal axes create such surfaces >50% of the time.

3.5. Chop Mark Terminology

As with any highly specialised discussion, terminology is important. Below is a list of terms used in our experimental study. The definitions below are compiled from the zooarchaeological and forensics literature on chop marks in conjunction with observations from this experimental study.

- Chop: a butchery mark created by high-speed compression forces inflicted from a sharpened wedge-shaped tool with the intention of severing a bone [48,54].
- Complete chop: a chop that severs the bone into two or more pieces [61].
- Incomplete chop: a chop that does not sever the bone but leaves a mark (deep or shallow) in the surface of the bone, often with an acute angle wedge fracture. This includes deep V-or irregular U-shaped grooves [48,61].
- Axis/kerf line: the final penetration point of the axe into the bone surface [51].
- Fracture: breakage of the bone with no visible chop mark characteristics [52].
- Kerf fracture: fracture or breakage extending from the axis/kerf line due to wedge action [52].
- Obtuse angle of chop: inferior side of chop when directed at 45° (see Figure 3) [56].

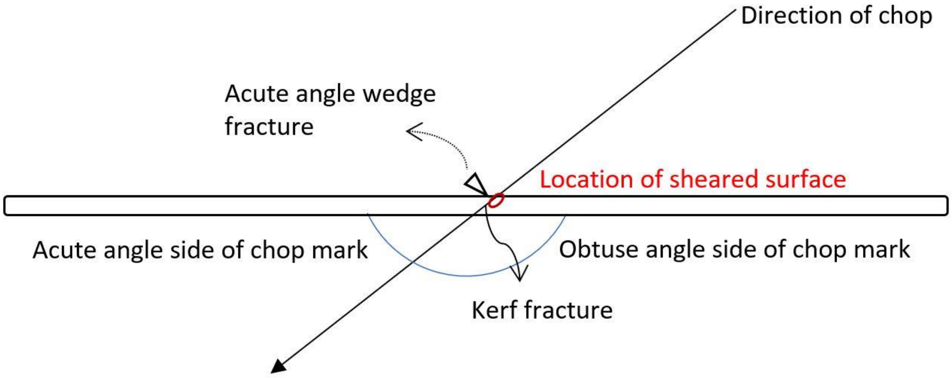

Figure 3. Schematic of chop mark characteristics based on [56].

- Acute angle of chop: superior side of chop when directed at 45° (see Figure 3) [56].
- Bit: The sharpened cutting edge of a wedge-shaped impact tool (axe).
- Sheared surface: a very clean, smooth, cut surface that extends into the bone for at least 3 mm [52].
- Crushing: fractured bone surface pushed into the chop mark by the force of impact [52].

- Acute angle wedge fracture: a small segment of bone on acute side of chop that fractures and is pushed out of chop mark (see Figure 3) [56].

4. Experimental Tests

A total of 117 chop marks were created by the five replica axes. These accumulated because of the following series of controlled chopping tests.

4.1. Test 1

The first test was designed to avoid the issue of variation in chop mark diagnostic criteria due to differential density by bone types and age of individual. Bone density varies depending on the element, age, and taxon. Consequently, each axe type was initially tested on a one-inch-thick flat plank of soft wood (pine). These chop marks did not go all the way through the wood and resulted in preservation of both sides of the chop marks.

Each axe was tested three times at different locations on a pine wood plank. The tests were: (1) a single strike, (2) two strikes in the same location, and (3) multiple strikes in the same location with the aim of severing the board. The marks on each board were labelled, photographed, and examined both macro and microscopically. Chop marks on bone are often only partially preserved due to high rates of fragmentation during the chopping process.

In order to better define the morphology of the chop marks, we chose pine wood as a medium since it would not fragment and both sides of the chop mark would be preserved. We were concerned that the varying morphology, structure, and density of bone would not allow for a clear definition of chop mark morphology (which is borne out by the experiments). While it is recognised that a pine wood plank is not an exact replacement for bone, it is a suitable substitute for this type of experiment.

A pine wood plank is relatively soft and has a more uniform shape and internal structure and density than bone. As such, it is much less susceptible to complete fragmentation upon impact. Chop mark morphology is not affected by the shape and/or density and best preserves the morphology of both the acute and obtuse sides of the mark. Thus, the pine wood chop marks should be considered as “ideal” examples of preserved incomplete chop marks.

The pine wood examples help to highlight specific aspects of axe morphology that leave distinctive and differential impact traces (mark shape, degree of crushing, and apex line morphology) as the entire mark is preserved. Therefore, we suggest caution in directly extrapolating the results of the pine wood test for bone to incomplete chop marks on bones, as the soft and consistent structure of wood preserves these characterises more consistently than bone.

4.2. Test 2

In this experiment, each axe was tested on a separate sheep (*Ovis aries*) cranium. The chops were aimed to divide the cranium into anterior and posterior halves along the coronal plane posterior to the horn core base. This location would expose the brain and is a common location for chop marks within the Göltepe faunal assemblage.

4.3. Test 3

The axes were next tested on cattle (*Bos taurus*) ribs. Cattle ribs were chosen for their dense and relatively consistent structure, particularly in the middle of the shaft. The mid-shaft rib segments were chopped multiple times. None of the axes penetrated the bone when struck at a 90° angle that was perpendicular to the long axis of the bone. The axes were then tested on the rib specimens again, but at an orientation that was parallel to the long axis of the bone.

Once again, each specimen was chopped at 90° and 45° angles, with a minimum of three impact incidences. With this orientation, the edge of each axe blade was able to penetrate the bone’s surface, with the exception of the chipped stone axe (Axe 4), which merely bounced off the surface of the bone. Axe 5 (chipped stone) was not used in Test 3 as the axe head suffered significant damage in the second test and was not included in subsequent tests. It is described here to demonstrate the difficulty in using such an instrument for chopping dense bone.

4.4. Test 4

In this test, pig (*Sus scrofa*) ribs were selected for testing to determine if there is a difference between them and cattle ribs (above). Chops were directed only in a perpendicular orientation to the long axis of the bones since they were too small to be tested otherwise. Many of the chops on the pig ribs successfully either severed or shattered the rib bones.

4.5. Test 5 and 6

Tests 5 and 6 are described together since they exhibit similar characteristics and problems. Test 5 was on pig long bones (ulna and radius), while Test 6 was on pig vertebrae. These tests created analytical issues as substantial amounts of meat covered the bone when it was chopped. This prevented the axe from striking the bone in some cases. This was only discovered once the bones were de-fleshed and cleaned. In other words, butchers may sometimes chop carcasses without damaging the bone.

4.6. Test 7

The final series of tests were conducted on a variety of white-tailed deer (*Odocoileus virginianus*) long bones. The four limbs were used to separately test the four remaining axes. These tests were successful in chopping through the flesh and striking the bone, particularly along the middle of the bone shafts.

5. Experimental Chop Mark Classification

5.1. Complete Chops vs. Incomplete Chop Marks

Within the study of chop marks, it is crucial to differentiate between complete and incomplete chop marks as they create distinct but partially overlapping marks that are not always comparable. A complete chop mark successfully severs the bone, whereas an incomplete chop mark does not. The benefit of an incomplete chop is that both sides of the mark are preserved and available for analysis. An incomplete chop is not always a deep mark, and it often presents itself as a slight indentation or imprint of the bit on the bone's surface. Shallow incomplete marks (surface marks) can sometimes resemble slice marks, although they are often deeper and do not have the indicative slicing drag on one side of the mark.

In this study, these very shallow marks are referred to as surface marks and are not included within the larger sample of complete marks. Deeper incomplete marks that penetrate more than a few millimetres into the surface of the bone, but do not sever the bone, leave either a deep V or U shape. Deep incomplete marks often share enough characteristics with complete chops to be included within the complete chopped sample.

For deep incomplete marks to be classed within the complete chop marks, they must exhibit a discernible entry point and deep enough radial cracking to understand how the bone would have broken apart or fractured if more force was applied. This overview of our experimental study focuses primarily on complete chop marks as they constitute the majority of the experimental sample, and illustrate the diagnostic criteria for identifying axe morphology, production type, and raw material more effectively than incomplete marks. An in-depth review of the incomplete marks will be published elsewhere.

5.2. The 5-Point Fragmentation Scale for Complete Chops

The experimental chop marks are incredibly variable. As such, the experimental chop marks are grouped and discussed according to specific characteristics regardless of axe material type. The most common characteristic of all the experimental chops is fragmentation/breakage. This ranges from nil to severe. The purpose of a chop is to separate the bone into two separate pieces by high-speed directed force. The high speed and high force directed into the bone is meant to cause controlled breakage at a specific location. An ideal chop mark, from a functional perspective, creates two separate pieces with no/low fragmentation on either side of the chop.

Understanding fracture patterns is vital as we found that fragmentation took distinct forms that can be classified on a scale from 1–5. The degree of control over how the bones broke apart is discussed according to these groups. Thus, high levels of fragmentation and crushing register lower on the scale (1–2), and low levels of fragmentation and crushing register higher on the scale (4–5). Some marks exhibit extremely low fragmentation, particularly on one side of the mark. These smooth surfaces are referred to as sheared surfaces.

A fragmentation scale is a necessary metric of intensity as it facilitates comparison within a highly variable group of marks by assigning them to defined groups based on shared attributes. The groups are based on the intensity of fragmentation seen in the experimental sample. A total of 88 experimental chop marks were grouped according to this scale.

6. Experimental Results

6.1. Fragmentation Class 1

A Class 1 chop mark on the fragmentation scale occurs when the axe does not penetrate the surface of the bone. Crushing at the place of impact is often the only indicator of the chop (Figure 4). Without the crushing at the edges, this type of chop mark is indeterminable from natural breakage as the bone often fractures into multiple pieces causing uncontrolled breakage. As a consequence, it is easy to misidentify this fragmentation pattern as natural breakage or as non-diagnostic fractures often created by hammerstone percussion [34]. However, Class 1 chop marks do not have similar diagnostic traits as hammerstone percussion as they do not exhibit percussion notches, percussion flakes, percussion marks, shaft cylinders, or impact flakes [34].

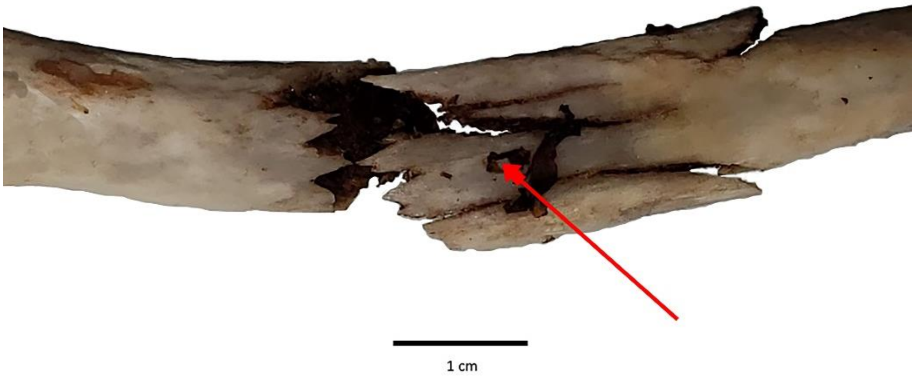

Figure 4. Class 1 experimental chop mark made by the ground stone axe on a pig rib (cBI 91) with uncontrolled breakage and crushing at the place of impact (arrow indicates the place of impact).

This type of ambiguous fracture might also be misidentified as rib peeling. Rib peeling is caused by extreme bending that causes the bone to snap or break. The low and slow pressure of bending force rarely causes complete separation of the bone segments and often leaves small bits of fibrous fresh bone still attached that must then be peeled away. The major distinctive morphological trait of peeling are missing strips of outer cortical bone that radiate from a broken or snapped edge [62,63]. Although some Class 1 chop marks may appear as snap breakage, they do not have the distinctive peeled grooves. No chop marks by any of the experimental axes created marks that mimic rib peeling.

Class 1 chop marks are challenging to identify and could be either misidentified, classed as natural breakage, or missed entirely. Identifying a Class 1 chop mark outside of an experimental setting should be done with caution as there are many natural and cultural agents that can produce seemingly similar fragmentation. Class 1 chop marks created by broad ground stone axes may also be confused with bashes made by hammerstones unless conchoidal fractures are present.

Twenty percent of the complete chops are Class 1. The ground stone axe produced most of the Class 1 marks (67%), chipped stone axes produced 11% of the marks, and copper axes produced 22%. The bronze metal axe did not produce such marks. It is likely that Class 1 chops are underreported because the chop will not be visible if the bone completely fractured upon impact and left no discernible traces. Chopping the bone with meat and periosteum still on the bone often prevents the axe from directly impacting the bone. In the experiment, it was impossible to know if a strike caused complete fragmentation until the bones were de-fleshed and processed. This adds to the difficulty in identifying this mark.

6.2. Fragmentation Class 2

This class of fragmentation is what we call "a somewhat defined chop mark" (Figure 5). Class 2 chop marks are less likely to be confused with natural breakage than Class 1, but still consist purely of breakage rather than cutting. The breakage is slightly more controlled than in a Class 1 mark and the point of impact/straight line where breakage begins is visible. This type of chop can exhibit significant crushing and breakage. Class 2 marks are also difficult to recognise outside of an experimental setting.

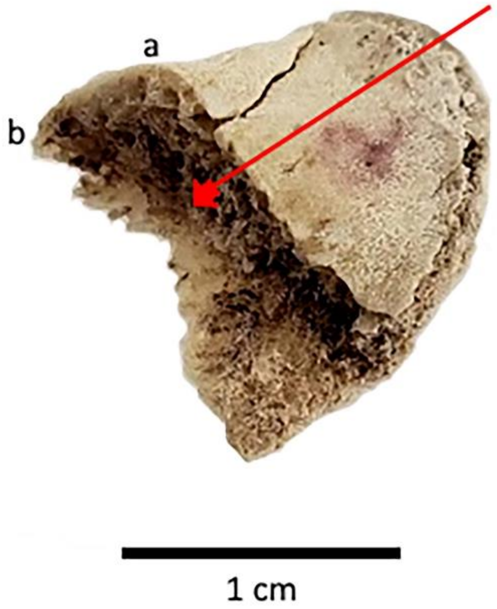

Figure 5. A Class 2 experimental chop mark made by the ground stone axe on a pig vertebra (cBI 82). The arrow indicates the direction of impact, (a) place of impact (relatively straight line where breakage begins), and (b) stepped breakage (somewhat controlled).

Of the experimental chops, 19% were a Class 2, and all axes created at least a few Class 2 marks. The ground stone axe once again produced most of these marks at 47%, but copper also produced a significant 35% of the marks. The bronze axe created far fewer (12% of the marks), while the chipped stone axe only created 6% of the Class 2 marks. An interesting pattern emerges with the metal axes regarding this category. In rare cases when both sides of the chop mark were preserved and it was possible to fit them back together, the acute side of the mark was often identified as a Class 2 mark, while the obtuse side was anywhere between a 2 and a 5. Thus, both sides of the same chop mark do not necessarily present identical fragmentation patterns, and this deviation is often more apparent with the metal axes.

6.3. Fragmentation Class 3

A Class 3 chop mark on the fragmentation scale is a well-defined chop mark that clearly represents intentional severing (Figure 6). This chop mark will often have mild crushing at the point of impact and a relatively straight line of breakage below. A Class 3 mark consists of very controlled breakage with a clearly identifiable entry point. Rather than the axe chopping through the bone, the axe produced extremely clean and controlled breakage.

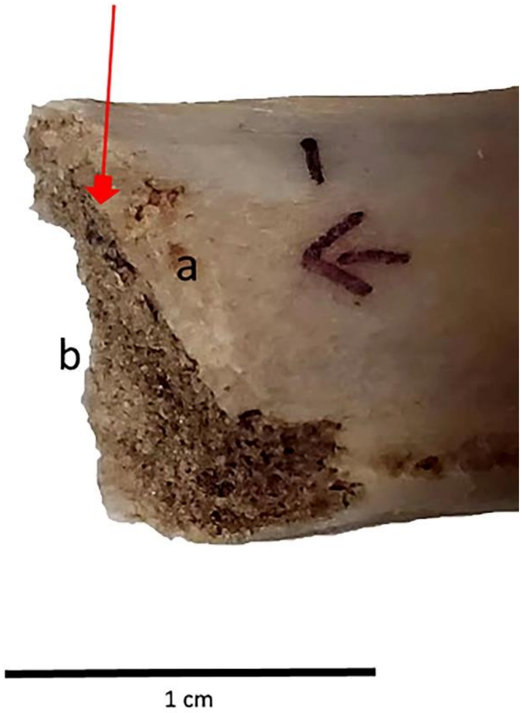

Figure 6. Class 3 experimental chop mark made by the bronze axe on a pig rib (cBI 13); (a) light crushing at place of impact (arrow indicates the place and direction of the impact), and (b) controlled breakage.

Class 3 is the most common mark created by the experimental axes with 33% of all experimental chops placed in this category. The chipped stone axe only produced one mark comparable to a Class 3. The majority of these marks were created by the copper axe (45.5%), followed by equal proportions by the bronze (27%) and ground stone axes (27%). A similar pattern was observed with the metal axes in this category as in the previous category where the two best examples of Class 5 shearing on the obtuse side are mirrored on the acute side with a Class 3. In contrast, the cleanest Class 3 marks created by the ground stone axe are mirrored on the acute side with heavy fragmentation (Class 1). In sum, Classes 1–3 describe breakage patterns due to impact rather than cutting of the bone.

6.4. Fragmentation Class 4

A Class 4 chop mark on the fragmentation scale is the first to exhibit shearing. Shearing is the absence of fragmentation, meaning that the axe entered the bone by cutting it and did not cause the chopped surface of the bone to break apart or flake off (except for a kerf fracture). A Class 4 mark can have light crushing, will almost always have a kerf fracture exit point, and will have at least some mild [shearing (a 3–10 mm sheared surface). A sheared surface is clean and smooth with no undulation or macroscopic parallel striations on the planar surface of the chop mark. A sheared surface is extremely identifiable (Figure 7). Class 4 marks have a smaller sheared surface area than a Class 5 because the axe does not penetrate/cut as deep into the bone before kerf fracture occurs.

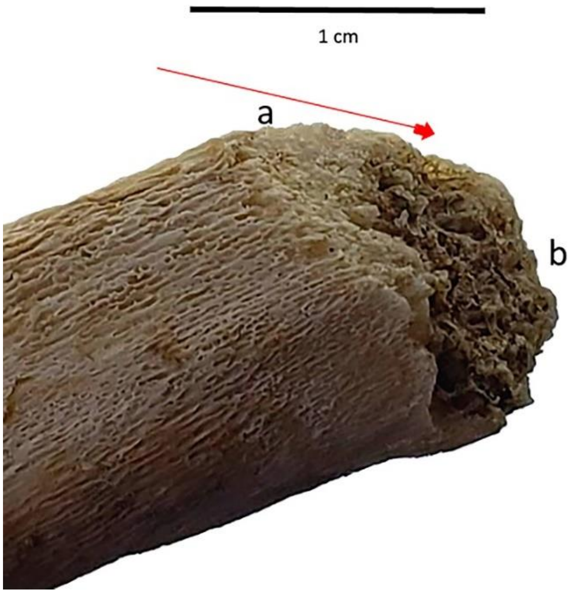

Figure 7. Class 4 experimental chop mark made by the copper axe on a pig rib (cBI 41); (a) beginning of sheared surface, (b) controlled breakage after kerf fracture. The arrow indicates the direction of the chop.

All experimental Class 4 chops were made by metal axes and represent 17% of the total number of complete chop marks. The copper axe produced most (60%) of the Class 4 marks, while the bronze axe created the other 40%.

6.5. Fragmentation Class 5

A Class 5 chop mark on the fragmentation scale exhibited little or no crushing with moderate to extensive shearing (Figure 8). These are highly recognisable marks that have a clean entry point, smooth chopped surface with no macroscopic striations, and an exit fracture. The fracture pattern of a Class 5 chop mark is extremely controlled, and fragmentation is limited to only the kerf fracture at the base of the chop mark. It is also possible for a sheared surface to continue completely through the entire bone. If a sheared surface continues completely through the bone, there will be no kerf fracture and the smooth cut surface will extend the entire length of the chop mark.

Only 11% of the experimental chops are a Class 5. Of these, two marks are made by the copper axe and the remainder by the bronze axe. This is the rarest type of mark found within the experimental sample. Figure 9 shows a breakdown of the fragmentation patterns created by each axe type, while Figure 10 is a schematic representation of chop mark Classes (1–5).

6.6. The Chipped Stone Axes (Axes 4 and 5)

The chipped stone axes produced the most unique marks in comparison to the other axes. The undulating and non-uniform cutting edge produced a ‘wavy’ chopped surface with uneven macroscopic striations running parallel to the direction of the axe impact. This ‘wavy’ pattern was also noted by Olsen and Shipman [64] in their experiments with obsidian choppers. Due to the uneven cutting surface of the tool, our chipped stone axes did not create a clean sheared chopped mark on bone. Only rarely did this tool penetrate the surface of the bone further than a few millimetres. The chipped stone axes created only seven complete chops that were clear enough to be analysed after processing, and all of the marks ranged between Classes 1 and 3 on the Fragmentation Scale (Table 4).

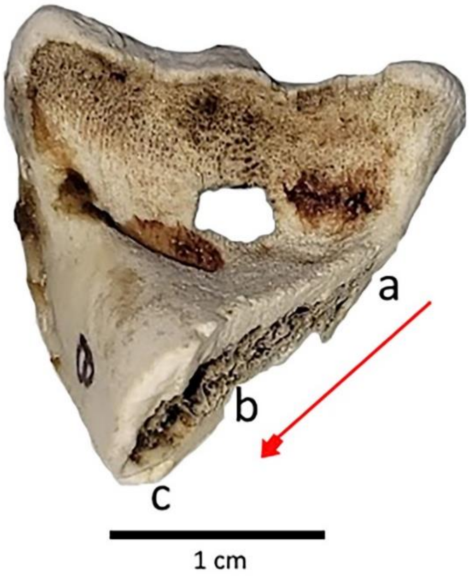

Figure 8. Class 5 chop mark made by the bronze axe on deer humerus (cBI 26); (a) place of impact (beginning of sheared surface), (b) kerf fracture (end of sheared surface), and (c) controlled breakage. The arrow indicates the direction of the axe.

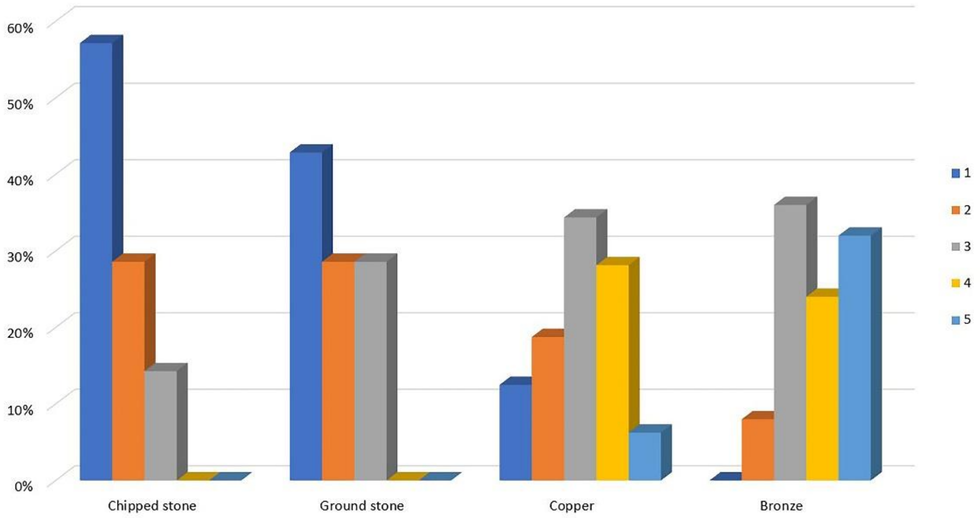

Figure 9. Frequency distribution of experimental axe types (left to right: chipped stone, ground stone, copper, and bronze) by Fragmentation Class (1–5).

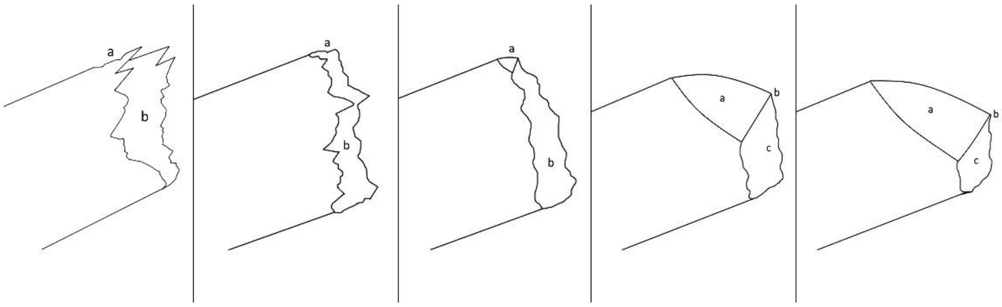

Figure 10. Schematic of Class 1–5 chop marks from left to right. Class 1—(a) severe crushing

(ambiguous point of impact) and (b) uncontrolled breakage. Class 2—(a) moderate crushing and/or visible impact location and (b) uncontrolled breakage. Class 3—(a) clear place of impact with little/no crushing and (b) controlled breakage. Class 4—(a) small (<5 mm) sheared surface with little/no crushing, (b) kerf fracture, and (c) controlled breakage. Class 5—(a) extensive (>10 mm) sheared surface with no crushing, (b) kerf fracture, and (c) controlled breakage

Table 4. Frequency distribution of experimental chipped stone axe chop marks by Fragmentation Class.

Fragmentation Class	Number of Chop Marks
1	4
2	2
3	1
Surface	6
Total	13

The chipped stone axes struggled in the chopping experiments. While they could successfully sever soft (not fully ossified or fused) bone, such as the juvenile *Ovis* skull, and break bone with very little meat covering the bone, they could not sever or break ossified bone with a hard cortex (especially from large mammals) or when a substantial layer of meat covered the bone. Further, such tools are generally ineffective butchery tools since they have fragile cutting edges (bits) that can easily break when applied with high-speed force. We found that chipped stone axes are only capable of successfully chopping softer materials (flesh and unossified bone) and are difficult to use as butchery tools otherwise.

Almost half (46%) of the chipped stone marks are incomplete surface marks that did not result in any fragmentation. The incomplete marks are morphologically unique compared to any other axe type. These marks are punctuated, with various depths along the apex. The marks and their apexes are not straight as they reflect the irregular (wavy) cutting bit of the chipped stone tool. Chipped stone axes require many strikes to the bone before fragmentation occurs, which results in a much higher percentage of incomplete marks compared to all other axe types. The morphology of these incomplete marks is indicative of only this material and manufacture style and resemble "peck marks" (Figure 11). These "peck marks" are more indicative of chopping activity with a chipped stone axe than the actual fragmentation of the bone.

The chipped stone axe heads were in a constant state of remodelling as they fractured, dulled, or re-sharpened themselves during the experiments. Similar to, but less extreme than the experimental results of Kononenko et al. [60], our chipped stone axe bits never produced the exact same signature morphology twice. It is the irregularity and inconsistency of these marks that are the distinctive characteristic of chipped stone axe chop marks.

Stout et al. [65] found very similar marks at the Lower Palaeolithic site of Boxgrove (UK). The marks still have microscopic pieces of flint embedded into the surface and are thought to be made by Acheulean hand axes approximately 500,000 years ago. Our experimental results resemble both the marks from Boxgrove and the experimental marks described by Olsen and Shipman [64].

6.7. The Ground Stone Axe (Axe 3)

The ground stone axe created the least distinct marks of any axe type and only produced marks between a 1–3 on the Fragmentation Scale (Table 5). The ground stone axe produced the heaviest degree of crushing at the point of entry and rarely penetrated the surface further than a few millimetres before fragmentation occurred. A rough chopped surface with no macroscopic parallel striations is diagnostic for these chop marks. Many of the ground stone chop marks are difficult to recognise as chop marks due to their high level of fragmentation. Consequently, they are classed between a 1–3 on the Fragmentation Scale. Only a single mark out of the 32 ground stone chop marks had a relatively smooth point of entry. Since this relatively smooth surface is very small (2 mm) and the remainder of the bone is quite fragmentary, the mark is classed as a Class 3 and not a Class 4.

Figure 11. "Peck mark" created by the chert chipped stone axe on a deer radius (cBI 106).

Table 5. Frequency distribution of experimental ground stone axe chop marks by Fragmentation Class.

Fragmentation Class	Number of Chop marks
1	12
2	8
3	8
Surface	4
Total	32

More extensive crushing is noted on all ground stone chop marks relative to those created by the metal axes. Crushing is further exaggerated on bones with a dense outer cortex (large mammals) as opposed to more delicate elements, such as the vertebrae and crania of smaller individuals. A slight increase in crushing is also noted as the tool dulled slightly after each impact.

All ground stone chops on the pig ribs were directed into the bone at approximately a 45° angle to test the shearing capabilities. Only a single rib bone was divided into two separate sections, while the majority fragmented into three or four pieces, and the most heavily fragmented rib broke into 12 pieces. No sheared surfaces were identified. The chop mark with a relatively smooth entry (mentioned above) was unintentionally directed into the bone at a very low angle (approx. 15°).

A ground stone axe creates significant crushing and fragmentation on both sides of the chop marks and many of the marks would be difficult to identify as chop marks within an archaeological assemblage. When chop marks are more identifiable (a Class 2 or 3), the other side of the mark is often very fragmented and would not be identifiable as a chop mark outside of an experimental setting. Thus, many chops made by ground stone axes are likely to be missed in an archaeological assemblage due to a lack of discernible features.

The ground stone axe produced noticeably fewer surface marks compared to the chipped stone axe. These incomplete marks are much more indicative of the raw material and manufacture than the complete chop marks. Ground stone surface marks are more often a wide U-shape rather than V-shape, with a pitted, relatively straight apex line (see Figure 12 for a comparison of incomplete marks on wood). Identification of the pitted apex line can be aided by examination under a low powered microscope.

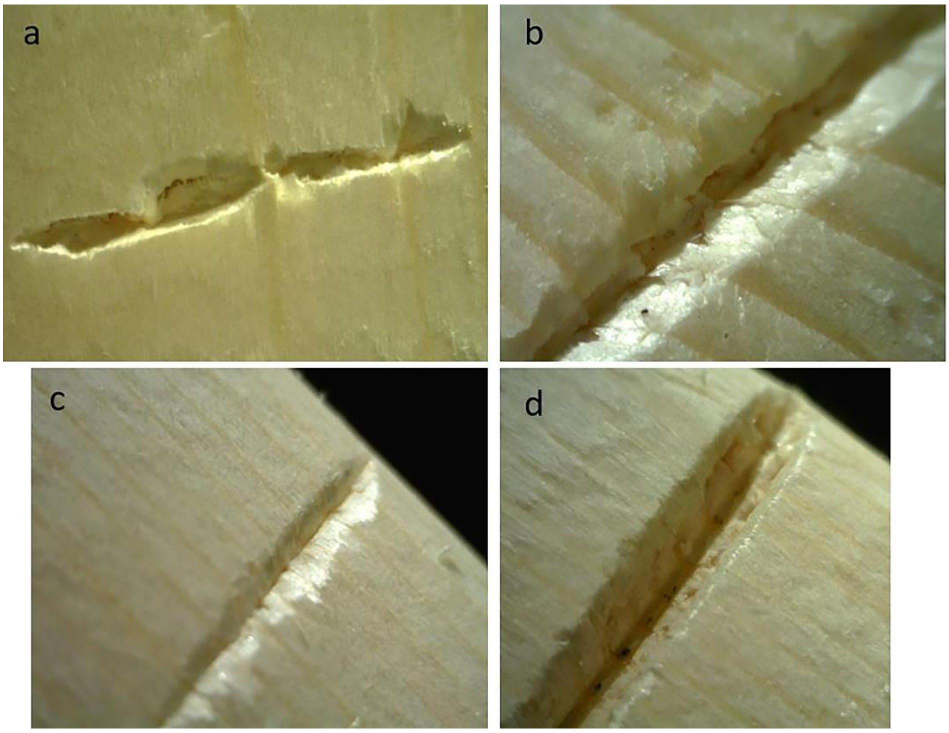

Figure 12. Photographs of incomplete (not fully severed) marks on wood; (**a**) flint chipped stone, (**b**) ground stone, (**c**) copper, and (**d**) bronze.

6.8. The Copper Axe (Axe 2)

The copper axe produced the most variable range of chop marks with multiple chops assigned to each fragmentation class. The copper axe produced more Class 3 marks than any other fragmentation Class. The second highest group was Class 4, and the third most frequent group was Class 2 (Table 6). Most chops demonstrated light crushing at the point of entry, while only a few exhibited heavy crushing.

Table 6. The frequency distribution of experimental copper axe chop marks by Fragmentation Class.

Fragmentation Class	Number of Chop Marks
1	4
2	6
3	11
4	9
5	2
Surface	9
Total	41

Of the 41 copper chop marks, 17% had some level of shearing on the chopped surfaces. The sheared surfaces averaged 5 mm in length, with a single sheared surface closer to 10 mm in length. While the level of shearing was not extensive, it was present and macroscopically recognisable. Shearing only occurred when the bone was struck at a 45° angle, as opposed to a 90° angle.

Most chop marks made by the copper axe were recognisable on both sides of the chopped surface. Only 9.7% of the marks were highly fragmented (Class 1), which suggests that complete chop marks made by copper axes are more likely to be recognised than those created by ground stone axes. The copper axe created significantly less crushing at the place of impact than the ground stone axe. The exception to this is with the dense *Bos taurus* (cattle) ribs where the degree of crushing and the morphology of the marks were similar to the ground stone. The copper axe struggled to cut through dense bone and caused significant damage (crushing) to dense bone.

The wide variety of fragmentation classes created by the copper axe highlights the importance of analysing the entirety of a chopped assemblage as no single macroscopic trait is diagnostic of this material type. The copper axe can produce sheared surfaces but is also capable of creating very fragmented chops and varying degrees of crushing. Copper is a relatively soft material and the edge (bit) continually dulled, deformed, and required resharpening. The inability of copper to consistently retain a sharp cutting edge enabled an increased variability in fragmentation classes and crushing at the point of impact. Therefore, a chopped assemblage (complete marks) created primarily by copper axes will exhibit all types of fragmentation classes (sheared and non-sheared) along with the presence of moderate to mild crushing.

Incomplete surface marks made up 21% of the copper chop marks. The copper axe created V-shaped surface (incomplete) marks. The apex lines were straight and did not exhibit the pitting seen in the marks created by the ground stone axe. The walls of the mark exhibited some fragmentation/crushing and were not as cleanly defined as with examples created by the bronze axe (see Figure 12 for a comparison of incomplete marks on wood).

6.9. The Bronze Axe (Axe 1)

The bronze axe created 30 chop marks, but five (16%) were shallow surface marks. The bronze axe created deep V-shaped surface/incomplete marks. The surface marks varied in depth from 1 mm to almost 1 cm and always had a straight, non-pitted apex similar to those from the copper axe (Figure 12). However, the walls of the bronze axe surface marks were not fragmented and exhibited little to no crushing.

The bronze axe created 25 complete chop marks and was the only axe to produce no Class 1 marks (Table 7). The bronze axe created the least amount of crushing at the point of entry compared to all other axe types, and it was the only axe to produce more sheared than non-sheared marks. The shearing on some of the chop marks was extensive with one sheared surface continuing almost completely through the bone (Figure 8). The fragmentation caused by the bronze axe was more controlled than any other axe type, often resulting in only two fully severed pieces of bone when completely chopped through. The bronze axe was the only axe type capable of cleanly penetrating the hard and dense outer bone surface of the fully ossified *Bos taurus* ribs and *Sus scrofa* long bone shafts without creating crushing at the point of entry.

Table 7. The frequency distribution of experimental bronze chop marks by Fragmentation Class.

Fragmentation Class	Number of Chop Marks
2	2
3	9
4	6
5	8
Surface	5
Total	30

6.10. Morphological Differences between Metal and Stone Chop Marks

Complete (fully severed) chops make up most of the experimental assemblage. These range from a mass of tiny, fragmented pieces to perfectly smooth chopped surfaces where the bone is divided into only two pieces. While the rate of fragmentation within a chopped assemblage is generally associated with the axe material type, all axe materials produced multiple types of fragmentation patterns. The stone axes created more limited patterns of fragmentation than the metal axes. While the stone axes are sometimes able to divide the bone into only two separate pieces, they always create uneven or fragmented breakage on both sides of the chop mark, often with crushing at the entry point. Even with the more controlled ground stone chop marks, the chopped surface always exhibits fragmentation within the mark itself and has no sheared surfaces.

Metal axes produce a wider variety of fragmentation patterns compared with the stone axes. Both the copper and bronze axe created some marks similar to the ground stone axe (Class 1–3) but also created clean sheared surfaces with very low rates of fragmentation (Class 4–5). Metal axes are much more likely to create sheared surfaces when the bone is struck at a 45° angle as opposed to a 90° angle.

In this study, the copper axe produced fewer instances of shearing compared with the bronze axe. This is likely due to the differential hardness between the two materials. The copper axe also produced heavier crushing at the point of impact. The copper axe was never as sharp even though both tools were sharpened with the same metal hand file. The copper axe also did not retain a sharp edge for as long as the bronze axe and required repeated sharpening.

The definitive morphological characteristic of metal axe marks is shearing or the absence of fragmentation on the obtuse chopped surface. Shearing is the result of cutting rather than breakage and is only found on Class 4 and 5 chop marks. None of the stone axes created Class 4 or 5 chop marks, meaning that no sheared surfaces were created by stone axes. While breakage can create a relatively flat surface, it cannot create a smooth/cut surface. The problem with this morphological characteristic is that not all chops made by metal axes create sheared surfaces. Only 27% of the experimental chops created by the copper axe exhibited sheared surfaces, and 47% of the chops created with the bronze axe exhibited sheared surfaces. Shearing was also limited to one side of the chop mark. As noted previously, a sheared mark always produces an opposing side that is never higher than a Class 2 or a 3.

Although shearing did not appear on all chops made by metal axes, it was never associated with chop marks made by stone axes. This is due to the two major variables: width and sharpness [56]. The width of an axe determines how deep the axe can penetrate into the bone tissue before causing the bone to split, either at the kerf or completely [52]. If the axe is quite wide, it does not have the ability to penetrate further than the relatively short portion that was sharpened before it splits the bone as a wedge. This results in breakage at the point of impact rather than cutting through the bone (Figure 13).

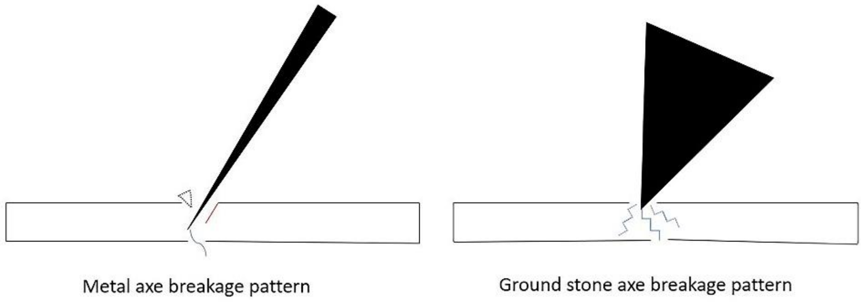

Figure 13. Schematic of metal vs. ground stone fragmentation pattern.

The sharpness of the axe determines how cleanly the axe can enter the surface of the bone. The sharper and thinner the implement, the more concentrated the force that will continue down into the bone instead of spreading out over the surface of the bone. This will create a smoother and deeper chopped surface. Humphrey and Hutchinson [52] found that metal axes, unlike thinner metal tools—such as machetes and cleavers—sometimes push bone material into the chop mark itself. This is defined as crushing, and crushing is more likely when both the width of the tool is increased and the sharpness decreased.

Our experiments found that these criteria are exaggerated in dense bone (large mammal), especially with respect to the crushing and sharpness of the bit. An axe must be thin, very sharp, and strong to cut into the surface of dense (large mammal) cortical bone without creating medium/heavy crushing at the point of impact. In contrast, a thin, moderately sharp and strong axe can cut into medium mammal cortical bone with relatively little crushing. We found the degree of crushing at the place of impact is a function of variables related to sharpness of the axe bit.

The ground stone axe was very successful at splitting the bone; however, it could not cut through the bone without causing splintering and fragmentation on both sides of the chop. A thinner and sharper stone axe does have the ability to penetrate further into the bone as demonstrated by the thin Knife River Flint axe. However, the thin and sharp cutting edge of the Knife River Flint axe head was too fragile to handle the high-speed impact needed for chopping and shattered almost immediately. Although untested, a very thin ground stone axe might also be at risk for significant damage while chopping dense bone material.

Our ground stone axe did not retain its sharp cutting edge for long. The cutting bit consistently chipped off until it reached an equilibrium where the edge was stable enough in relation to the amount of force inflicted upon it. Therefore, the functional form of the tool must be dictated by the structural integrity of the material. Earlier Neolithic ground stone axe forms are considerably thinner than those found in the LC and the EBA. These thinner/sharper forms may have the ability to cut into the bone without causing significant damage to the tool. However, this remains untested.

The fragmentation patterns of the complete chop marks reflect the shape and structural integrity of the tool rather than the raw material. Hence, thick and wide-edged (and consequently dull) axes produce fragmented chops with no shearing. Thin, narrow-edged (and consequently sharp) axes can also produce this type of mark when directed into the bone at a 90° angle. However, when they are used even at a slightly deviating angle, thin sharp-edged axes produce marks with significantly less fragmentation and a sheared surface on the obtuse side. Wenham (1989) also concluded that axe thickness is the major variable for determining the amount of crushing at the surface and the depth the axe can penetrate bone tissue before fracture occurs. As such, it is important to understand tool variability for the period in question before applying the results of this or any experimental study to an archaeological faunal assemblage.

The application of the method is dependent on a sample of chop marks rather than individual chop marks as all axe material types can create multiple fragmentation classes. Chop marks created by metal axes (thin and sharp) cluster between 2–5 on the fragmentation scale, while stone axes (wide and dull) cluster between 1–3 on the fragmentation scale. Individual chop marks should never be considered as indicative, definite evidence of a particular tool material type or be used in place of the overall fragmentation pattern. The fragmentation scale allows for outliers, and this is essential when each material has such a wide range of morphological possibilities.

6.11. Criteria for Identifying Complete Chop Marks

Identifying chop marks that fall lower than a Class 3 on the fragmentation scale is difficult as these marks often do not display a clear point of entry. Without knowing where the axe struck the bone, it is almost impossible to argue that the breakage displayed is in fact created by an axe and not by other depositional or taphonomic processes. A point of entry is defined either by concentrated crushing, a relatively straight line from which breakage begins or the beginnings of a sheared surface.

Any of these criteria indicate the place of impact from a wedge-shaped tool. As this experimental study shows, metal axes create these diagnostic criteria more frequently than stone axes. This means that there can be a clear bias (if one is not careful) toward the identification of metal axe marks as opposed to stone axe marks (especially ground stone) in the archaeological record. Close attention to the placement of high fragmentation could be referenced in relation to ethnographic butchery mark placement see [1]. However, without direct evidence for the butchery marks themselves, this remains only an anecdotal inference.

7. The Zooarchaeological Sample

7.1. Regional Setting

The case study for this experimental project is the Late Chalcolithic/Early Bronze Age site of Göltepe, Turkey (4400–1900 BCE). Göltepe was a mountain village located in the south-eastern corner of the central Anatolian plateau, nestled amidst the Taurus Mountains (Figure 14). Located on the top of a steep hill, the 5 ha village is within sight of the Kestel tin mine located on the neighbouring hill [66]. Early Bronze Age Göltepe was a specialised metal production site, specifically tin (for a detailed description of the tin production process at Göltepe see [67]). There is no evidence for either copper, iron, or gold production at Göltepe during the Early Bronze Age [68].

Figure 14. Map showing the geographic location of Göltepe and the Kestel mine site within modern day Turkey.

It is interpreted as a first-tier metal production site, meaning that Göltepe was a location associated with extraction, grinding, smelting, and the creation of ingots, which would then be traded and or transported to larger centres [69,70]. Tin is an essential component of bronze and is a relatively rare element on earth. Before the discovery of the Kestel tin mine and its associated processing village at Göltepe, it was assumed that tin was imported into Anatolia from the east as it was during the Middle Bronze Age.

Recent geologic, isotopic, and archaeological investigation now indicates that tin was/is locally mined in Anatolia during the Early Bronze Age [70–72]. There is little evidence for the production of finished metal goods at Göltepe apart from a few simple tool moulds for axes, chisels, and ingots. While no finished metal axes were found, the few copper chisels are the only metal tools recovered from at EBA Göltepe [73,74].

7.2. EBA Anatolian Axes

The Early Bronze Age (c. 3000–2000 BCE) in Anatolia is a particularly unique period for axe types as metal (copper, arsenical-copper, and bronze) co-existed with older stone types. As a result, the simple identification of a chop mark on archaeological bone cannot be inherently linked to a specific material type without further experimental work. Four types of axes were common in EBA Anatolia. These are: (1) Chalcolithic style flat axes cast in an open face mould, (2) shaft-hole style battle axes cast using the lost-wax technique, (3) crescent-shaped axes cast in a bivalve mould, and (4) ground stone shaft-hole style axes ([35] (p. 84), [36,58,64], [75] (p. 55)).

While the chipped stone tool industry is often assumed to have declined during the EBA with the introduction of bronze metallurgy, this was not always the case, particularly regarding quotidian activities such as animal butchering. Chipped stone slicing tools continue to be used through the EBA and only begin to decline much later in the Bronze Age. This is particularly true wherever obsidian is abundantly available, including at Göltepe and other sites located near obsidian sources [41,45]. Nonetheless, in general, the range of chipped stone tool types becomes much more restricted and simplistic, and there is a perceived increase in ad hoc/single use stone tools [76]. This pattern is also observed in the southern Levant and often attributed to the increased availability of metal tools [58].

The EBA was a period of non-standardised axes within a society that accepted both new and old forms of this multi-purpose tool. The ratio of stone to metal axes in the EBA is the reverse of the pattern seen in the LC, in that stone axes became the exception rather than the standard. While stone axes, both chipped and ground (votive), disappear completely from the southern Levant after the EB I [58], ground stone axes continued to persist in a limited capacity across Anatolia throughout the EBA [35,36].

7.3. The Chopped Assemblage from Göltepe

The chopped assemblage from EBA Göltepe is comprised of 779 individual chop marks. All primary and secondary context EBA faunal material from Göltepe were examined for evidence of chopping, and 8.86% of the total Number of Identified Specimens (NISP) exhibit one or more chop mark(s). Most chop marks are found on medium mammals (87%), and only 8% are found on large mammals. The sample is primarily comprised of adult (40%) and sub-adult (38%) specimens with smaller frequencies (22%) of chop marks found on juvenile individuals. Chop marks are found on specimens across all EBA phases (EB I, II, and III) at Göltepe (See Yener 2021 for a full description and interpretation of phasing at EBA Göltepe).

Much of the chopped assemblage is comprised of complete chop marks (87%). An incredible 94% of the complete *Chopped Butchering Incidence* (cBI 523) are assigned to Classes 3–5. A butchering incidence is when there is one or more marks made at the same location for the same goal [9,38]. Of these marks, 31.5% (cBI 173) are assigned to Class 3, 37% (cBI 204) are assigned to Class 4, and 26% (cBI 146) to Class 5. (Figure 15) Crushing at the point of entry is minimal for all chop marks considered to be Class 3 and above and is observed in less the 1% of all Class 3 and Class 4 marks. No crushing is observed on any Class 5 marks. (See Figure 15 for fragmentation Class frequencies of complete chop mark incidences).

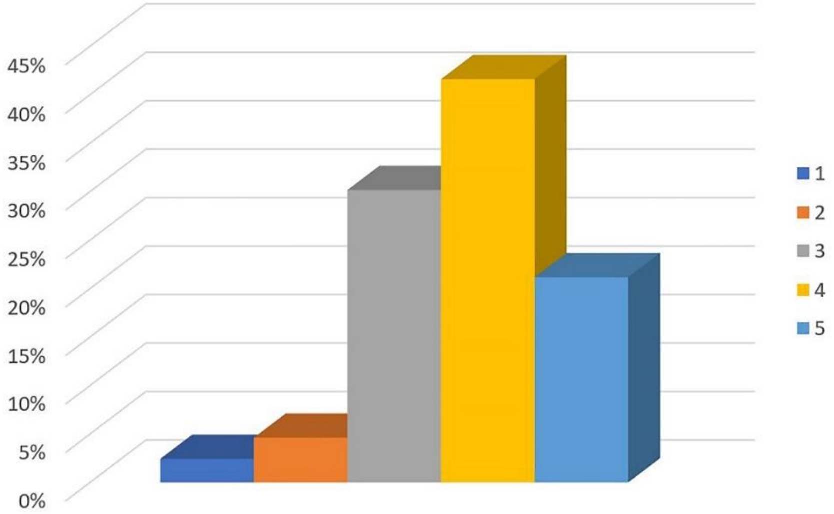

Figure 15. Frequency histogram of all EBA Göltepe chop marks classified by Fragmentation Classes 1–5.

The overall fragmentation pattern does not vary when chop marks are compared according to size class or age. Class 4 chop marks are always the most common with both Class 3 and Class 5 much more frequent than both Classes 1 and 2.

The Class 5 marks within the Göltepe assemblage are remarkable. The depth of the sheared surface before kerf fracture is measurable for 35.5% of the complete Class 5 chop marks, and some of these chop marks are exceptionally deep. The depths ranged from 5 mm up to 30 mm, and averaged 8–15 mm. This is well beyond the depths created by the experimental sample and indicates than an extremely thin and sharp axe created these chop marks. See Figure 16 for examples of chop marks from Göltepe.

Figure 16. Examples of Class 5 complete chop marks from Göltepe (left to right: *Ovis/Capra* vertebra, MRN 2299, bone 13; *Capra hircus* horn core, MRN 3433, bone 35; *Ovis/Capra* vertebra, MRN 2299, bone 12).

Incomplete marks make up only 13% of the chopped assemblage from Göltepe. Many of these marks are quite deep, and due to the depth, as well as the 45° angle rather than a 90° angle, the apex line is only visible on 3.6% of the incomplete marks. Of the visible apex lines, the vast majority are straight and narrow with no macroscopic or microscopic pitting. However, due to weathering and root etching, some incomplete marks are not appropriate for assessment. No “peck marks” were observed on or around any of the identified chop marks.

8. Discussion

Based on comparison with the experimental results from the five axe types, most of the chop marks from EBA Göltepe were likely created by metal axes. This conclusion is based on both our experimental results in conjunction with the specific axe types available during the period of investigation. LC/EBA Anatolia used very wide ground stone axes, and the evidence for chipped stone axes is extremely limited.

The experimental study shows that wide ground stone axes create very fragmented chops and are extremely unlikely to cut through the bone before fracture occurs. While it is possible that ground stone axes created some of the more fragmented chop marks, the overall pattern of chop mark fragmentation from Göltepe closely resembles the fragmentation distribution created by the experimental metal axes, especially the bronze axe. The exceptionally low levels of fragmentation within the chopped assemblage from Göltepe, along with the depth of axe penetration, lack of crushing, and intensity of shearing could not be created by EBA style stone axes (see Figure 2).

The depth of the marks found on the Göltepe chopped assemblage strongly suggests that they may have been made by bronze or possibly arsenical-copper axes. While it may be possible that a heavier pure copper axe might be able to cut into bone deeper than our experimental copper axe did, it does not negate the observation that our copper axe caused much more crushing at the point of impact compared to the bronze axe. The lack of crushing at the point of entry on the majority of the Göltepe chopped assemblage strongly suggests that the axes used were made from a harder alloy material.

Based on the chop marks, the use of metal axes at EBA Göltepe did not increase through time. This suggests that the adoption of metal axes as the preferred tool in butchery dismemberment took place either at or before the Chalcolithic/EB I transition in south central Anatolia. Although Göltepe may have had unique access to metal resources as a metal production site, it is unlikely that the residents of Göltepe existed in a social bubble. Late Chalcolithic/EBA I Göltepe was a seasonal metal production site, and for part of the year, the residents must have resided elsewhere [68]. Since metal axes were used consistently in butchery at Göltepe during this period, metal axes were presumably also in use at other (nearby) sites as well.

The recovered metal finds from Göltepe are not overly impressive, nor do they suggest that metal tools were extensively used in everyday situations. The EBA metal finds mainly consist of small items of personal adornment, such as pins, rings, and bracelets. The only functional items recovered are two metal chisels, an awl, and a needle [73]. The enormous quantity of ground stone tools (mainly grinding stone and pounders) and simple flakes found across the site from all EBA Periods, suggests that stone tools were the preferred utilitarian tool material.

Slice mark analysis on the faunal assemblage supports the theory that metal tools were not extensively used in the EBA, nor were they integrated as a part of everyday butchery activities [45]. The analysis of the chop marks on the faunal material from all EBA phases at Göltepe indicates that this was not the case. While metal knives were not used, metal chopping instruments were extensively used in butchery. Metal chop marks on butchery remains are found across all periods and are not reserved to specific contexts.

Metal chop marks on faunal material are found in almost all contexts, including pit houses, dirt and stone lined pits, outdoor activity areas, Terraced Buildings 1 and 2, stone foundation buildings, stone installations, thermal installations, and middens. This suggests that all butchers had access to metal chopping instruments and that they were an everyday tool available to the general population of EBA Göltepe. Thus, even though metal axes are not physically present in the archaeological record at the site, their residual remains can be identified in the animal bone assemblage.

The extensive use of metal chopping instruments in butchery provides new evidence for how metal functioned and was used within EBA Anatolian society. While metal in the EBA was clearly a prestige material used by the elite classes to differentiate themselves as powerful leaders, metal was not exclusively reserved for the elite class. Metal was used, traded, and consumed by both elite and non-elite individuals. Investigation into the adoption of new technologies and the differential use of metals by elite and non-elite can benefit from butchery analysis, as it may not be self-evident in the material culture.

9. Conclusions

The experimental research presented here is intended as the beginnings of a systematic method (that can be utilised even in field settings) to aid in the recognition of chop marks on archaeological bone. It focuses on and highlights the macroscopic differences between chop marks made by stone and metal chopping instruments.

Chop marks are an incredibly varied grouping of butchery marks. Chop marks can present as U- or V-shaped marks, complete fragmentation, uncontrolled breakage, controlled breakage, and sheared (cut) surfaces. Therefore, it is important to look at the overall fragmentation patterns of the chopped assemblage for variables, such as crushing, degree of fragmentation, depth of chop mark, and shearing. These characteristics generally correspond to the width and sharpness of the cutting edge on the instrument [52,56].

Metal axes create relatively low levels of crushing compared to stone axes and are more likely to cut through the bone instead of breaking the bone. These observations are important as complete chop marks are often defined as a “flat, planar surface” [50]. It is clear from this experimental study that this is a very narrow definition that describes only the obtuse side of some metal chop marks and/or chop marks created by very thin and sharp axes.

Understanding the macroscopic variability within the broad category of chop marks has also revealed the need for further work and experimentation on this subject, especially regarding the microscopic differentiation of chop marks created by different types of metal or stone axes. A more detailed analysis of this topic may require the two overarching material groups (metal and stone) to be microscopically investigated individually, as one material class typically presents as breakage, and the other typically presents as a cut surface.

While our goal is to define macroscopic diagnostic criteria to identify the axe shape, production type, and raw material, which are useful in field settings, subjectivity in descriptive morphological characteristics can be problematic regarding how each researcher interprets the criteria for analysis [21,24]. In this experimental study, we identified key criteria for identifying chop marks and described how these criteria generally present according to material type. Deep Learning algorithms can be programmed to detect these traits more consistently than the human eye and help to remove some subjectivity [22,74,75]. We suggest this as an additional way forward for distinguishing chop marks made by different material types.

Detailed discussions of chop marks on archaeological faunal assemblages are rare but are an important component of butchery studies as demonstrated by the case study from Göltepe. Axes do not necessarily (nor should they be expected to) follow the same technological trajectory as knives. It is a mistake to assume that the replacement of stone tool technologies used in animal butchery occurred with all technologies simultaneously with the advent of the Bronze Age.

Some types of tools were rapidly adopted and replaced older technologies (chopping tools), while others were retained for long periods of time (slicing tools) [7,43,47]. When investigating a time when there was access to diverse types of butchery tools made from different raw materials, it is essential to be aware of how each present as macroscopic marks on bone as more than one type may be in use. In conclusion, chop marks do not always present themselves as flat or sheared surfaces, and a host of attributes must be considered when identifying the raw material and the type of butchering instrument.

Author Contributions: Conceptualization, methods, investigation, writing—T.R.O. and H.J.G.; formal analysis—T.R.O.; curation, funding acquisition, project administration validation—H.J.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by grants and institutional support from the Social Sciences and Humanities Research Council of Canada, the University of Manitoba, and St. Paul's College to Haskel J. Greenfield.

Acknowledgments: We would like to thank Aslihan Yener and Allan Gilbert for their permission to analyse and publish the data, Tina L. Greenfield for help in sorting out the stratigraphy at the site, and the anonymous reviewers for their comments. Finally, we would like to thank Gord Hill for graciously lending his chert and flint biface tools for the project, Curtis Link for helping to shape the ground stone axe head, and Jon Ross for his help in conducting the butchery experiments. Any errors are the responsibility of the authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Binford, L.R. *Bones: Ancient Men and Modern Myths*; Academic Press: New York, NY, USA, 1981.
2. Lyman, R.L. Archaeofaunas and butchery studies: A taphonomic perspective. *Adv. Archaeol. Method Theory* **1987**, *10*, 249–337.
3. Seetah, K. Meat in history-the butchery trade in the Romano-British period. *Food Hist.* **2004**, *2*, 19–33. [CrossRef]
4. Seetah, K. Butchery as a tool for understanding the changing view of animals: Cattle in Roman Britain. In *Just Skin and Bones? New Perspectives on Human-Animal Relations in the Historical Past*; British Archaeological Reports, International Series 1410; Pluskowski, A., Ed.; BAR: Oxford, UK, 2005; pp. 1–8.
5. Greenfield, H.J. Slicing cut marks on animal bones: Diagnostics for identifying stone tool type and raw material. *J. Field Archaeol.* **2006**, *31*, 147–163. [CrossRef]
6. Seetah, K. Multidisciplinary approach to Romano-British cattle butchery. In *Integrating Zooarchaeology*; Maltby, M., Ed.; Oxbow: Oxford, UK, 2006; pp. 111–118.
7. Greenfield, H.J. "The Fall of the House of Flint": A zooarchaeological perspective on the decline of chipped stone tools for butchering animals in the Bronze and Iron Ages of the southern Levant. *Lithic Technol.* **2013**, *38*, 161–178. [CrossRef]

8. Beller, J.A.; Greenfield, H.J.; Levy, T.E. The butchered faunal remains from Nahal Tillah, an EB I Egypto-Levantine settlement in the southern Levant. In *Archaeozoology of Southwest Asia and Adjacent Areas XIII: Proceedings of the 10th ICAZ-ASWA Conference, Nicosia, Cyprus, 4–10 June 2017*; Daujat, J., Hadjikoumis, A., Berthon, R., Eds.; Lockwood Press: Columbus, OH, USA, 2022; pp. 61–80.
9. Greenfield, H.J.; Brown, A. 'Making the cut': Changes in butchering technology and efficiency patterns from the Chalcolithic to modern Arab occupations at Tell Halif, Israel. In *Bones and Identity: Zooarchaeological Approaches to Reconstructing Social and Cultural Landscapes in Southwest Asia (Proceedings of the ICAZ-SW Asia Conference, Haifa, Israel, 23–28 June 2013)*; Marom, N., Yeshurun, R., Weissbrod, L., Bar-Oz, G., Eds.; Oxbow Press: Oxford, UK, 2016; pp. 273–291.
10. Greenfield, H.J.; Beller, J.A.; Levy, T.E. Butchering technology during the Early Bronze Age I: An examination of microscopic cut marks on animal bones from Nahal Tillah, Israel. In *Tell It in Gath: Studies in the History and Archaeology of Israel. Essays in Honor of A. M. Maeir on the Occasion of his Sixtieth Birthday, Ägypten und Altes Testament. Studien zu Geschichte, Kultur und Religion Ägyptens und des Alten Testaments; Band 90*; Shai, I., Chadwick, J.R., Hitchcock, L., Dagam, A., McKinny, C., Uziel, J., Eds.; Zaphon: Münster, Germany, 2018; pp. 20–40.
11. Greenfield, H.J.; Beller, J.A.; Gaastra, J. Changes in butchering technology and efficiency patterns between the Early and Middle Bronze Ages from Tell Zirā'a, Jordan. In *Tall Zirā'a, The Gadara Region Project (2001–2011) Final Report: Early and Middle Bronze Age (Strata 25–17)*; Vieweger, D., Häser, J., Eds.; Deutsches Evangelisches Institut: Wuppertal, Germany, 2021; Volume 3.
12. Courtenay, L.A.; Yravedra, J.; Aramendi, J.; Maté-González, M.Á.; Martín-Pereaf, D.M.; Uribelarreaf, D.; Baquedano, E.; González-Aguilerac, D.; Dominguez-Rodrigo, M. Cut marks and raw material exploitation in the Lower Pleistocene site of Bell's Korongo (BK, Olduvai Gorge, Tanzania): A geometric morphometric analysis. *Quat. Int.* **2019**, *526*, 155–168. [CrossRef]
13. Domínguez-Rodrigo, M. Distinguishing between apples and oranges: The application of modern cut-mark studies to the Plio-Pleistocene (a reply to Monahan). *J. Hum. Evol.* **1999**, *37*, 793–800. [CrossRef] [PubMed]
14. Domínguez-Rodrigo, M. On cut marks and statistical inferences: Methodological comments on Lupo & O'Connell. *J. Archaeol. Sci.* **2003**, *30*, 381–386.
15. Dominguez-Rodrigo, M.; Barba, R. A study of cut marks on small-sized carcasses and its application to the study of cut-marked bones from small mammals at the FLK Zinj site. *J. Taphon.* **2005**, *3*, 121–134.
16. Greenfield, H.J. The origins of metallurgy: Distinguishing stone from metal cut marks on bones from archaeological sites. *J. Archaeol. Sci.* **1999**, *26*, 797–808. [CrossRef]
17. Greenfield, H.J. Distinguishing metal (steel and low-tin bronze) from stone (flint and obsidian) tool cut marks on bone: An experimental approach. In *Experimental Archaeology: Replicating Past Objects, Behaviors, and Processes. British Archaeological Reports, International Series 1035*; Mathieu, J.R., Ed.; Archaeopress: Oxford, UK, 2002; pp. 35–54.
18. Pante, M.C.; Muttart, M.V.; Keevil, T.L.; Blumenschine, R.J.; Njau, J.K.; Merritt, S.R. A new high-resolution 3-D quantitative method for identifying bone surface modifications with implications for the Early Stone Age archaeological record. *J. Hum. Evol.* **2017**, *102*, 1–11. [CrossRef] [PubMed]
19. Pickering, T.R.; Hensley-Marschand, B. Cutmarks and hominid handedness. *J. Archaeol. Sci.* **2008**, *35*, 310–315. [CrossRef]
20. Shipman, P. Application of scanning electron microscopy to taphonomic problems. *Ann. N. Y. Acad. Sci.* **1981**, *375*, 357–385. [CrossRef] [PubMed]
21. Domínguez-Rodrigo, M.; Saladié, P.; Cáceres, I.; Huguet, R.; Yravedra, J.; Rodríguez-Hidalgo, A.; Patricia, M.; Antonio, P.; Juan, M.; Clara, G. Spilled ink blots the mind: A reply to Merrit et al. (2018) on subjectivity and bone surface modifications. *J. Archaeol. Sci.* **2019**, *102*, 80–86. [CrossRef]
22. Domínguez-Rodrigo, M.; Cifuentes-Alcobendas, G.; Jiménez-García, B.; Abellán, N.; Pizarro-Monzo, M.; Organista, E.; Baquedano, E. Artificial intelligence provides greater accuracy in the classification of modern and ancient bone surface modifications. *Sci. Rep.* **2020**, *10*, 18862. [CrossRef] [PubMed]
23. Yravedra, J.; Maté-González, M.Á.; Palomeque-González, J.F.; Aramendi, J.; Estaca-Gómez, V.; San Juan Blazquez, M.; García Vargas, E.; Organista, E.; González-Aguilera, D.; Arriaza, M.C. A new approach to raw material use in the exploitation of animal carcasses at BK (Upper Bed II, Olduvai Gorge, Tanzania): A micro-photogrammetric and geometric morphometric analysis of fossil cut marks. *Boreas* **2017**, *46*, 860–873. [CrossRef]
24. Merritt, S.R.; Pante, M.C.; Keevil, T.L.; Njau, J.K.; Blumenschine, R.J. Don't cry over spilled ink: Missing context prevents replication and creates the Rorschach effect in bone surface modification studies. *J. Archaeol. Sci.* **2019**, *102*, 71–79. [CrossRef]
25. de Gruchy, S.; Rogers, T.L. Identifying chop marks on cremated bone: A preliminary study. *J. Forensic Sci.* **2002**, *47*, 1–4. [CrossRef]
26. Tucker, B.K.; Hutchinson, D.L.; Gilliland, M.; Charles, T.M.; Daniel, H.J.; Wolfe, L.D. Microscopic characteristics of hacking trauma. *J. Forensic Sci.* **2001**, *46*, 234–240. [CrossRef] [PubMed]
27. Dominguez-Rodrigo, M.; Pickering, T.R.; Semaw, S.; Rogers, M.J. Cutmarked bones from Pliocene archaeological sites at Gona, Afar, Ethiopia: Implications for the function of the world's oldest stone tools. *J. Hum. Evol.* **2005**, *48*, 109–121. [CrossRef] [PubMed]
28. Horwitz, L.K.; Monchot, H. Choice cuts: Hominid butchery activities at the Lower Paleolithic Site of Holon, Israel. In *Archaeozoology of the Near East V: Proceedings of the Fifth International Symposium on the Archaeozoology of Southwestern Asia and Adjacent Areas held at Yarmouk University, Irbid, Jordan in 2000*; Buitenhuis, H., Choyke, A.M., Mashkour, M., Al-Shiyab, A.H., Eds.; ARC: Groningen, The Netherlands, 2002; pp. 48–61.
29. Perez, V.R.; Godfrey, L.R.; Nowak-Kemp, M.; Burney, D.A.; Ratsimbazafy, J.; Vasey, N. Evidence of early butchery of giant lemurs in Madagascar. *J. Hum. Evol.* **2005**, *49*, 722–742. [CrossRef] [PubMed]

30. Maltby, M. Chop and change: Specialist cattle carcass processing in Roman Britain. In *TRAC 2006: Proceedings of the 16th Annual Theoretical Roman Archaeology Conference, the University of Cambridge, Cambridge, UK, 24–25 March 2006*; Croxford, B., Ray, N., Roth, R., Eds.; Oxbow: Oxford, UK, 2007; pp. 59–76.
31. Soulier, M.-C. Exploring meat processing in the past: Insights from the Nunamiut people. *PLoS ONE* **2021**, *16*, e0245213. [CrossRef] [PubMed]
32. Blasco, R.; Domínguez-Rodrigo, M.; Arilla, M.; Camarós, E.; Rosell, J. Breaking bones to obtain marrow: A comparative study between percussion by batting bone on an anvil and hammerstone percussion. *Archaeometry* **2014**, *56*, 1085–1104. [CrossRef]
33. Haynes, G.; Krasinski, K.; Wojtal, P. A study of fractured Proboscidean bones in recent and fossil assemblages. *J. Archaeol. Method Theory* **2020**, *28*, 956–1025. [CrossRef]
34. Pickering, T.R.; Egeland, C.P. Experimental patterns of hammerstone percussion damage on bones: Implications for inferences of carcass processing by humans. *J. Archaeol. Sci.* **2006**, *33*, 459–469. [CrossRef]
35. Massa, M. Early Bronze Age burial customs on the central Anatolian plateau: A view from Demircihöyük-Sarıket. *Anatol. Stud.* **2014**, *64*, 73–93. [CrossRef]
36. Rosen, S.A. Arrowheads, axes, Ad Hoc, and sickles: An introduction to aspects to Lithic variability across the Near East in the Bronze and Iron Age. *Lithic Technol.* **2013**, *38*, 141–149. [CrossRef]
37. Şahoğlu, V.; Tuncel, R. New insights into the Late Chalcolithic of coastal western Anatolia: A view from Bakla Tepe, Izmir. In *Western Anatolia before Troy. Proto-Urbanisation in the 4th Millennium BC*; Horejs, B., Mehofer, M., Eds.; Austrian Academy of Sciences Press: Vienna, Austria, 2014; pp. 65–82.
38. Greenfield, H.J.; Cheney, T.; Galili, E. A taphonomic and technological analysis of the butchered animal bone remains from Atlit Yam, a submerged PPNC site off the coast of Israel. In *Bones and Identity: Zooarchaeological Approaches to Reconstructing Social and Cultural Landscapes in Southwest Asia (Proceedings of the ICAZ-SW Asia Conference, Haifa, Israel, 23–28 June 2013)*; Marom, N., Yeshurun, R., Weissbrod, L., Bar-Oz, G., Eds.; Oxbow Press: Oxford, UK, 2016; pp. 89–112.
39. Saidel, B.; Erickson-Gini, T.; Vardi, J.; Rosen, S.A.; Maher, E.F.; Greenfield, H.J. Egypt, copper, and microlithic drills: The test excavations at Rogem Be'erotayim in western Negev. *Mitkufat Haeven (J. Isr. Prehist. Soc.)* **2006**, *36*, 201–229.
40. Greenfield, H.J.; Greenfield, T.L. Butchering technology in Middle Bronze Age Ashkelon. In *Final Reports of the Leon Levy Expedition to Ashkelon: Ashkelon 6: The Middle Bronze Age Ramparts and Gates of the North Slope and Later Fortifications*; Stager, L.E., Master, D.M., Schloen, J.D., Eds.; Harvard Semitic Museum Publications and Eisenbrauns: University Park, PA, USA, 2018; pp. 509–520.
41. Greenfield, H.J.; Marciniak, A. Retention of old technologies following the end of the Neolithic: Microscopic analysis of the butchering marks on animal bones from Çatalhöyük East. *World Archaeol.* **2019**, *51*, 76–103. [CrossRef]
42. Lev-Tov, J.S.E.; Killebrew, A.E.; Greenfield, H.J.; Brown, A. Puppy sacrifice and cynophagy from early Philistine Tel Miqne-Ekron contextualized. *J. East. Mediterr. Archaeol. Herit.* **2018**, *6*, 1–30. [CrossRef]
43. Greenfield, H.J. Insufficient evidence for metal butchering marks at Tell el-Hesi during the Early Bronze Age: Critique of the analysis of microscopic grooves in 'Cultural Modification Analyses on Faunal Remains in Relation to Space Use and Direct Provisioning from Field VI EBIIIA Tell el-Hesi' by Kara Larson, James W. Hardin, and Sara Cody. *Palest. Explor. Q.* **2021**, *160*, 144–155.
44. Greenfield, H.J.; Brown, A.; De Miroschedji, P. Origins of metallurgy in the southern Levant: Microscopic examination of butchering marks on animal bones at Tel Yarmuth, Israel. In *Themes in Old World Zooarchaeology: From the Mediterranean to the Atlantic*; Albarella, U., Detry, C., Gabriel, S., Ginja, C., Pires, A.E., Tereso, J.P., Eds.; Oxbow Books: Oxford, UK, 2021; pp. 95–107.
45. Greenfield, H.J.; Chaput, T. Butchering technology at the early tin metal producing site of Göltepe. In *Tin Production at Göltepe: Excavations at an Early Bronze Age Mining Town in the Central Taurus Mountains, Turkey*; Yener, K.A., Ed.; Institute for Aegean Academic Press: Philadelpha, PA, USA, 2021; pp. 160–176.
46. Greenfield, H.J.; Marciniak, A. The emergence and transmission of metallurgical technology for subsistence activities in daily life in northern Europe: A microscopic zooarchaeological perspective. *J. Field Archael.* **2021**, *46*, 275–288. [CrossRef]
47. Greenfield, H.J. Monitoring the origins of metallurgy: An application of cut mark analysis on animals bones from the Central Balkans. *Environ. Archaeol.* **2000**, *5*, 119–132. [CrossRef]
48. Olsen, S.L. The identification of stone and metal tool marks on bone artifacts. In *Scanning Electron Microscopy in Archaeology. British*; Archaeological Reports, International Series 452; Olsen, S.L., Ed.; BAR: Oxford, UK, 1988; pp. 337–360.
49. Walker, P.L.; Long, J.C. An experimental study of the morphological characteristics of tool marks. *Am. Antiq.* **1977**, *42*, 605–616. [CrossRef]
50. Gifford-Gonzalez, D.P. *An Introduction to Zooarchaeology*; Springer: Berlin/Heidelberg, Germany, 2018.
51. Lewis, J.E. Identifying sword marks on bone: Criteria for distinguishing between cut marks made by different classes of bladed weapons. *J. Archaeol. Sci.* **2008**, *35*, 2001–2008. [CrossRef]
52. Humphrey, J.H.; Hutchinson, D.L. Macroscopic characteristics of hacking trauma. *J. Forensic Sci.* **2001**, *46*, 228–233. [CrossRef] [PubMed]
53. Knusel, C.; Outram, A.K. Fragmentation: The zonation method applied to fragmented human remains from Archaeological and Forensic contexts. *Environ. Archaeol.* **2004**, *9*, 85–99. [CrossRef]
54. Lynn, K.S.; Fairgrieve, S.I. Macroscopic analysis of axe and hatchet trauma in fleshed and defleshed mammalian long bones. *J. Forensic Sci.* **2009**, *54*, 786–791. [CrossRef] [PubMed]

55. Symes, S.A.; Chapman, E.N.; Rainwater, C.W.; Cabo, L.L.; Myster, S.M.T. *Knife and Saw Toolmark Analysis in Bone: A Manual Designed for the Examination of Criminal Mutilation and Dismemberment*; National Institute of Justice: Rockville, MD, USA, 2010.
56. Wenham, S.J. Anatomical interpretation of Anglo-Saxon weapon injuries. In *Weapons and Warfare in Anglo-Saxon England*; Hawkes, S.C., Ed.; Oxford University Press: Oxford, UK, 1989; pp. 123–139.
57. Hansen, S. Arsenic bronze: An archaeological introduction into a key innovation. *Eurasia Antiq.* **2021**, *23*, 139–162.
58. Rosen, S.A. *Lithics after the Stone Age: A Handbook of Stone Tools from the Levant*; Altamira Press: Walnut Creek, CA, USA, 1997.
59. Yener, K.A. (Ed.) *Tin Production at Göltepe: Excavations at an Early Bronze Age Mining Town in the Central Taurus Mountains, Turkey*; INSTAP (Institute for Aegean Academic Press): Philadelpha, PA, USA, 2021.
60. Kononenko, N.; Torrence, R.; White, P. Unexpected uses for obsidian: Experimental replication and use-wear/residue analyses of chopping tools. *J. Archaeol. Sci.* **2015**, *54*, 254–269. [CrossRef]
61. Lupo, K.D.; Fancher, J.M.; Schmitt, D.N. The taphonomy of resource intensification: Zooarchaeological implications of resource scarcity among Bofi and Aka forest foragers. *J. Archaeol. Method Theory* **2013**, *20*, 420–447. [CrossRef]
62. Pickering, T.R.; Domínguez-Rodrigo, M.; Heaton, J.L.; Yravedra, J.; Barba, R.; Bunn, H.T.; Musiba, C.; Baquedano, E.; Diez-Martín, F.; Mabulla, A. Taphonomy of ungulate ribs and the consumption of meat and bone by 1.2-million-year-old hominins at Olduvai Gorge, Tanzania. *J. Archaeol. Sci.* **2013**, *40*, 1295–1309. [CrossRef]
63. White, T.D. *Prehistoric Cannibalism*; Princeton University Press: Princeton, NJ, USA, 1992.
64. Olsen, S.L.; Shipman, P. Surface modification on bone: Trampling versus butchery. *J. Archaeol. Sci.* **1988**, *15*, 535–553. [CrossRef]
65. Stout, D.; Apel, J.; Commander, J.; Roberts, M. Late Acheulean technology and cognition at Boxgrove, UK. *J. Archaeol. Sci.* **2014**, *41*, 576–590. [CrossRef]
66. Yener, A.K. Background. In *Tin Production at Göltepe: Excavations at an Early Bronze Age Mining Town in the Central Taurus Mountains, Turkey*; Yener, A.K., Ed.; INSTAP (Institute for Aegean Academic Press): Philadelpha, PA, USA, 2021; pp. 1–8.
67. Earl, B.; Özbal, H. Early Bronze Age tin processing at Kestel/Göltepe, Anatolia. *Archaeometry* **1996**, *38*, 289–303. [CrossRef]
68. Yener, K.A. *The Domestication of Metals: The Rise of Complex Metal Industries in Anatolia*; Brill: Leiden, The Netherlands, 2000.
69. Yener, K.A. Summary and Conclusions. In *Tin Production at Göltepe: Excavations at an Early Bronze Age Mining Town in the Central Taurus Mountains, Turkey*; Yener, A.K., Ed.; INSTAP (Institute for Aegean Academic Press): Philadelpha, PA, USA, 2021; pp. 195–206.
70. Yener, K.A.; Kulakoğlu, F.; Yazgan, E.; Kontani, R.; Hayakawa, Y.S.; Lehner, J.W.; Dardeniz, G.; Öztürk, G.; Johnson, M.; Kaptan, E.; et al. New tin mines and production sites near Kültepe, ancient Kanesh in Turkey: A third millennium BC highland production model. *Antiquity* **2015**, *89*, 596–612. [CrossRef]
71. Yener, K.A. *Excavations at Kestel Mine, Turkey: The Final Season: 1996–1997 Annual Report*; The Oriental Institute of the University of Chicago: Chicago, IL, USA, 2012.
72. Yener, K.A. Revisiting Kestel Mine and Göltepe: The dynamics of local provisioning of tin during the Early Bronze Age. In *Ancient Mining in Turkey and the Eastern Mediterranean*; Ozbal, H., Yalcin, U., Pasamehmetoglu, G., Eds.; Atilim University: Ankara, Turkey, 2008; pp. 57–64.
73. Yener, K.A. Small finds. In *Tin Production at Göltepe: Excavations at an Early Bronze Age Mining Town in the Central Taurus Mountains, Turkey, Yener, A.K., Ed.*; INSTAP (Institute for Aegean Academic Press): Philadelpha, PA, USA, 2021; pp. 111–148.
74. Yener, K.A. Horizontal Exposures at Göltepe. In *Tin Production at Göltepe: Excavations at an Early Bronze Age Mining Town in the Central Taurus Mountains, Turkey*; Yener, A.K., Ed.; INSTAP (Institute for Aegean Academic Press): Philadelpha, PA, USA, 2021; pp. 23–74.
75. Massa, M.; McIlfatrick, O.; Fidan, E. Patterns of metal procurement, manufacture and exchange in Early Bronze Age northwestern Anatolia: Demircihüyük and beyond. *Anatol. Stud.* **2017**, *67*, 51–83. [CrossRef]
76. Yakar, J. *Reflections of Ancient Anatolian Society in Archaeology: From Neolithic Village Communities to EBA Towns and Polities*; Homer Kitabevi: Istanbul, Turkey, 2011.