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1 THE NEUMARK-NORD SITE

1.1 Discovery, geology, stratigraphy and chronology

The Neumark-Nord 1 (NN1) palaeobasin was discovered in 1985 by M. Thomae during opencast lignite mining in the Müheln quarry in the Geiseltal valley near Merseburg, Saxony-Anhalt, Germany (51°19'28"N, 11°53'56"E; **Figure 1**).

Geological and archaeological investigations of the basin were undertaken from 1985 to 1996, by a team led by D. Mania and M. Thomae. The work of the team provided detailed insights into the geology, palaeoecology and archaeology of the 24 ha large palaeobasin^{1,2}. In 1995, when investigations at NN1 were still ongoing, team members discovered a second, adjacent palaeobasin, Neumark-Nord 2 (NN2), just ~100 metres north-east of NN1.

The NN1 basin and its infill could be geologically documented by 35 NNW-SSE running sections, between 500-1500 m long (total length ca. 30 km)

that followed cuts made by the mining activities, which over time progressed in a west to east direction (ref.³: **Figure 12**). These cuts were made by excavator machines along three arbitrary levels: 102, 94 and 86 m above sea level (resp. 8, 16 and 24 meter below the surface; see **Figure 2**)³. Hence it was not only possible to record the stratigraphy, morphology, and the diachronic development of the basin in great detail, but also the stratigraphic position of all archaeological, palaeontological, and archaeobotanical finds recovered throughout the NN1 basin.

The formation of the NN1 and adjacent smaller NN2 basin (**Figure 1, 3**) was the result of isostatic movement related to lignite diapirism⁴. The basin structures themselves formed in Saalian till deposits and subsequently filled up with fine-grained sediments. The NN1 basin infill consisted of predominantly silt loams and peat deposits reaching a total thickness of 15 m, while the more clastic infill of the NN2 basin reached a total thickness of 10 m (**Figure 3**). The complete infill of both basins can,



Figure 1 Geographical position of Neumark-Nord 1 and 2. This map shows the situation after the quarry was inundated and turned into a recreational lake

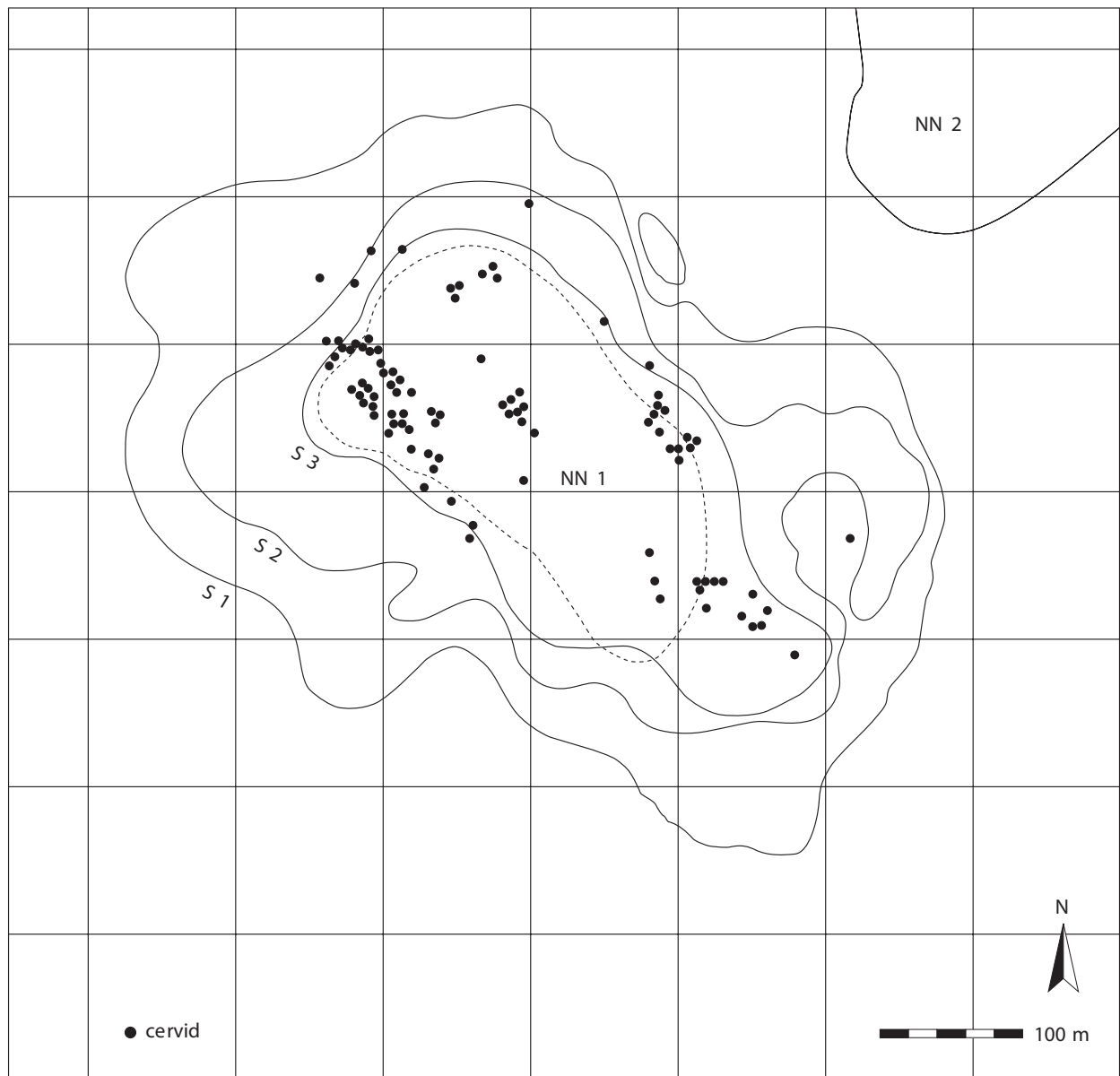


Figure 2 Spatial distribution of the cervids from unit 7 within the NN1 basin deposits. The contour lines indicate the extent of the basin deposits at three levels: 102 (S1), 94 (S2), and 86 m (S3) above sea level. The position of the NN2 basin is shown in the upper right corner.

on the basis of their stratigraphical position, pollen records, as well as geochronological analyses, which include TL of heated lithics, OSL of sediments, palaeomagnetism (NN2 only) and Amino Acid Racemisation studies of *Bithynia opercula*, be attributed to the Last Interglacial, the Eemian^{5,6}. The interglacial deposits are covered by a protective, thick blanket of Weichselian loess deposits. Apart from showing a typical Eemian vegetational succession and providing information on local vegetation conditions, the

NN1 and NN2 pollen records⁵⁻⁹ and the known duration of individual pollen assemblage zones (PAZ) of the Eemian^{10,11}, provide great temporal control for finds made in the basin deposits and the means to correlate the deposits of both basins on the scale of specific vegetation zones, i.e. within time constraints in the order of 1,000-2,000 years (**Figure 3**).

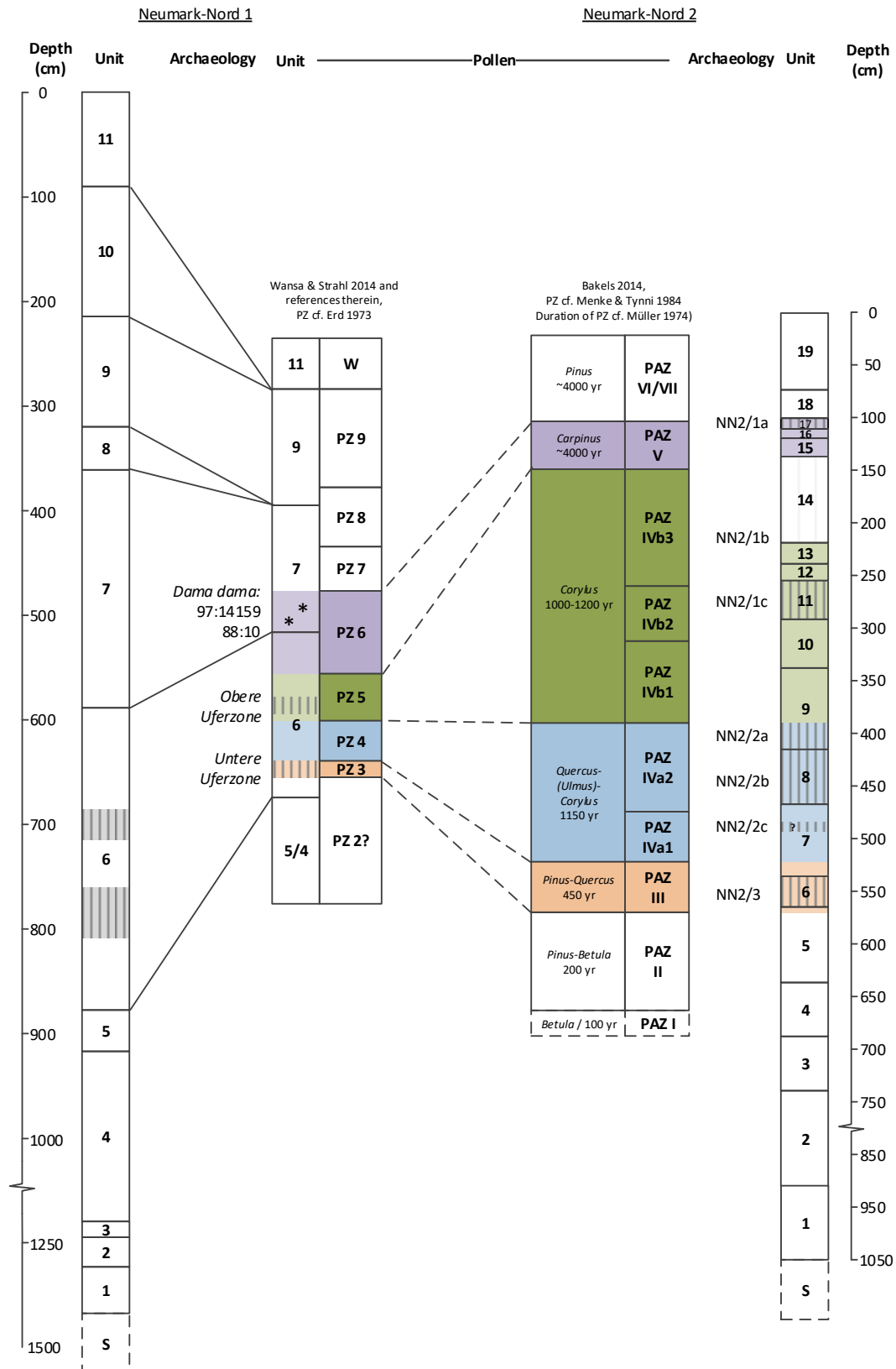


Figure 3 Stratigraphies of Neumark-Nord 1 (NN1) and Neumark-Nord 2 (NN2), correlated using pollen records⁷. The position of the main findlevels at NN1 and NN2 are indicated in grey vertical lines. Although cervids were recovered from units 4-7, this study focuses on unit 7, in which most of the individuals were found. The position of the fallow deer individuals with hunting lesions, No. 97:14159 and 88:10 are indicated. The archaeological record of both basins covers the early (PAZ I-IV) and middle part (PAZ V) of the Eemian.

1.2 Archaeological excavations

1.2.1 Neumark-Nord 1

Due to its large size and the ongoing large-scale mining activities, it was only possible to excavate small parts of the NN1 basin (ref.³: Figure 38). These excavations always took place under time pressure, sometimes actually in front of the digging machines. The archaeological fieldwork exposed two main find horizons at the basin margin (or *Uferzonen*) in lithostratigraphic unit 6 (**Figure 3**), which were systematically documented and which yielded faunal remains and lithic artefacts² dating to the early part of the Eemian (PAZ III to IVb). The lake margin position as well as the archaeological signature of these NN1 archaeological horizons are similar to find level NN2/2B¹² of the adjacent NN2 basin (**Figure 2**). Moving away from the basin margins, removal of the infill of the inner part of the NN1 basin by large quarrying excavators, supervised by Mania's team, yielded articulated and often complete skeletons of respectively cervids (n=211) and elephants (n= 71), together with the remains of smaller numbers of rhinos, aurochs, and carnivores (ref.³: Figure 28). These finds were made throughout the Eemian deposits, but were most abundant from mid-unit 6 to unit 7, correlating to PAZ III to VI. When such finds were exposed they were photographed, drawn, labelled, salvaged, and stored for subsequent analysis³. This process came to an end in 1996.

Despite the efforts of mining personnel and archaeologists carrying out the supervision, it was not possible to recover all skeletons or to recover them fully intact. Obvious reasons for this are the sheer size of the sections (8 m high), the quarrying equipment used (paddlewheel excavator with 1 m³ buckets), and the fact that the quarrying work continued during the night and under all weather conditions. Based on uninterrupted supervision during the excavation of 0.4 ha yielding 30 skeletons, and assuming similar densities in the rest of the basin area (total 8 ha; **Figure 2**, inner closed line), the total amount of cervid individuals may have approached 600³, rather

than the 211 presented in this study (section 2 – zooarchaeology).

1.2.2 Neumark-Nord 2

Having archaeological find levels of similar age as those of NN1 and located at less than 100 meters from NN1, the archaeological record of NN2 is of direct relevance to this study. Although the archaeology of this site has been published in detail elsewhere (e.g.^{6,12,13}), a short summary of the findings is presented here.

The small NN2 basin was situated at the margin of the quarrying area and remained largely untouched by mining activities after its initial discovery in 1995. NN2 was systematically excavated by the *Landesamt für Denkmalpflege und Archäologie Sachsen-Anhalt* (Germany) from 2003 onwards, and from 2006 to 2008 in cooperation with the Archaeological Research Centre and Museum for Human Behavioural Evolution MONREPOS of the *Römisch-Germanisches Zentralmuseum* (Germany) and the Faculty of Archaeology of Leiden University (The Netherlands). Because the NN2 excavations commenced after the quarrying ceased, they could cover large surfaces (492 m²) of the 2 ha-sized basin and excavate without the significant time pressure that affected the fieldwork at NN1. The excavations in 2003 focused on the uppermost find level NN2/0 (Early Weichselian)¹⁴, while in the next years activities were expanded to include NN2/1, NN2/2 and NN2/3, all three dating to the Eemian Interglacial^{5,6} (**Figure 3**). Of these, NN2/2 yielded the largest archaeological assemblage with more than 120,000 faunal remains and 18,000 lithic artefacts^{15,16}. The faunal remains attest to an MNI of at least 154 large herbivores, dominated by horse, red deer and bovids. These mostly heavily fragmented animal remains, accumulated over a period of maximally 500 years, show abundant traces of hominin modification.

2 ZOOARCHAEOLOGY NN1 CERVIDS

2.1 Introduction

This zooarchaeological study provides the results of a comprehensive taphonomic analysis of the NN1 cervid sample with a focus on the death of the cervids and their subsequent modification by biotic agents before final burial. The material of all find levels has been analysed, but because of the newly discovered anthropogenic modifications found on the cervids from unit 7 (see section 2.3.6, 2.3.7) discussed in the main text, the presentation of the results and the discussion will focus on the assemblage from this find level.

2.2 Material and methods

2.2.1 Assemblage composition

A major part of the sample used in the current study was already published by Mania³ and his work served as a point of departure for the current analysis. Of the sample published by Mania in 2010 (MNI=181), 142 individuals have been reanalysed, represented by mostly complete cervid skeletons and isolated elements as well as bone fragments collected from 1986 until 1996. The other 39 skeletons from units 6 and 7 were not available for reanalysis, either because they were not (n=2) or only partly (n=19) recovered, or not accessible (n=18). However, these individuals are still included here, based on the published data^{3,17}. Finally, this study encompasses 36 additional cervid skeletons from rescue excavations in 1987, 1996, 2002 and 2005, not presented in the latest study on this assemblage³. None of these additional skeletons could be attributed to a stratigraphical unit.

2.2.2 Methods

TAXONOMIC DETERMINATION, AGE AND SEX DETERMINATION, DETERMINATION OF SEASON OF DEATH

The NN1 cervid assemblage recovered up to 1996 was palaeontologically described by Pfeiffer in 1999¹⁷. On

the basis of her study, Pfeiffer defined *Dama dama geiselana*, a species that showed a greater length of the forelimb and exceeded the body height of recent European fallow deer (*Dama dama dama*) by 15-20%. *Dama dama geiselana* is considered a fast runner with excellent leaping abilities¹⁷.

Pfeiffer published data on the taxonomy as well as on the age and sex for the different individuals, including some information on season of death. Due to the presence of complete skeletons she was able to provide detailed insights into the ontogenetic development of male and female *Dama dama geiselana*. Data on age and sex of the cervid individuals is also provided by Mania³. In some cases these datasets diverge. The current analysis of the total assemblage took profit from Pfeiffer's ontogenetic observations and used her sources for the determination of species, age and sex¹⁷.

MINIMUM NUMBER OF INDIVIDUALS (MNI)

MNIs were calculated following Klein and Cruz-Urbe¹⁸ for each of the spatially separated find localities where an articulated skeleton was discovered. Bones from these individual sites have been salvaged and stored together. However, in several cases remains of more than one individual were represented at these localities. Based on skeletal element representation, osteometrical data and age determination, these bones could often be shown to represent not just a random association of isolated bones but rather substantial parts of an additional skeleton. In only a few cases an isolated bone could point to the presence of a further individual.

Information on 39 skeletons published by Mania³, which were not available for study, was included for the calculation of the MNI. Among them are 11 skeletons which have been described by Pfeiffer in detail¹⁷. Their data could therefore be included in the MNI calculations for age- and sex composition, but could not be verified by the current study.

BONE SURFACE MODIFICATIONS

Bone surfaces were studied using a Dino-Lite PRO digital microscope with a magnification of up to 200x and a Leica reflected-light microscope with a

Table 1 Minimum Numbers of Individuals (MNI) of the cervid assemblage for unit and species

	Unit 4		Unit 6		Unit 7		Unit 9		Unit indet.		Total	
	MNI	%	MNI	%	MNI	%	MNI	%	MNI	%	MNI	%
<i>Cervus elaphus</i>	1	50.0	5	17.2	22	16.2	1	100.0	9	20.9	38	18.0
<i>Dama dama geiselana</i>	1	50.0	24	82.8	106	77.9	0	0.0	29	67.4	160	75.8
Cervidae	0	0.0	0	0.0	8	5.9	0	0.0	5	11.6	13	6.2
Total	2	100.0	29	100.0	136	100.0	1	100.0	43	100.0	211	100.0

magnification of up to 32x. The presence and anatomical position of bone surface modifications have been recorded for each bone. These traces were identified as hominin induced cut-marks, anthropogenic fractures and carnivore modifications using comparative specimens in the taphonomic collection of the Archaeological Research Centre and Museum for Human Behavioural Evolution MONREPOS and diagnostic criteria published by Fernández-Jalvo and Andrews¹⁹.

WEATHERING

In order to estimate exposure time between the death of an animal and its final burial, bone weathering stages were documented following Behrens-meyer²⁰.

2.3 Results

2.3.1 Sample composition

The MNI for the cervid assemblage is 211, of which 160 (75.8%) can be attributed to *Dama dama geiselana*, 38 to *Cervus elaphus* (18.0%) and 13 (6.2%) only to family level (Table 1). The majority of the cervid material (64.5%) is coming from unit 7, the unit from which the perforated bones originate. Therefore, unless otherwise specified, the following focusses on the assemblage from this unit.

The assemblage composition for unit 7 reflects the composition of the total cervid assemblage from NN1 (Table 1). Red deer (MNI=22, 16.2%) and fallow deer (MNI=106, 77.9%) are represented. A fur-

Table 2 Minimum Numbers of Individuals (MNI) according to age and sex (juv. = juvenile, subad. = subadult) of cervids in unit 7.

	MNI total	%	<i>Cervus elaphus</i>	%	<i>Dama dama geiselana</i>	%	Cervidae	%
Males total	100	73.5%	17	77.3%	83	78.3%	0	0.0%
Juv./subad. males	22	16.2%	4	18.2%	18	17.0%	0	0.0%
Adult males	78	57.4%	13	59.1%	65	61.3%	0	0.0%
Females total	11	8.1%	2	9.1%	9	8.5%	0	0.0%
Juv./subad. females	9	6.6%	2	9.1%	7	6.6%	0	0.0%
Adult females	2	1.5%	0	0.0%	2	1.9%	0	0.0%
Sex indet.	25	18.4%	3	13.6%	14	13.2%	8	100.0%
Total	136	100.0%	22	100.0%	106	100.0%	8	100.0%

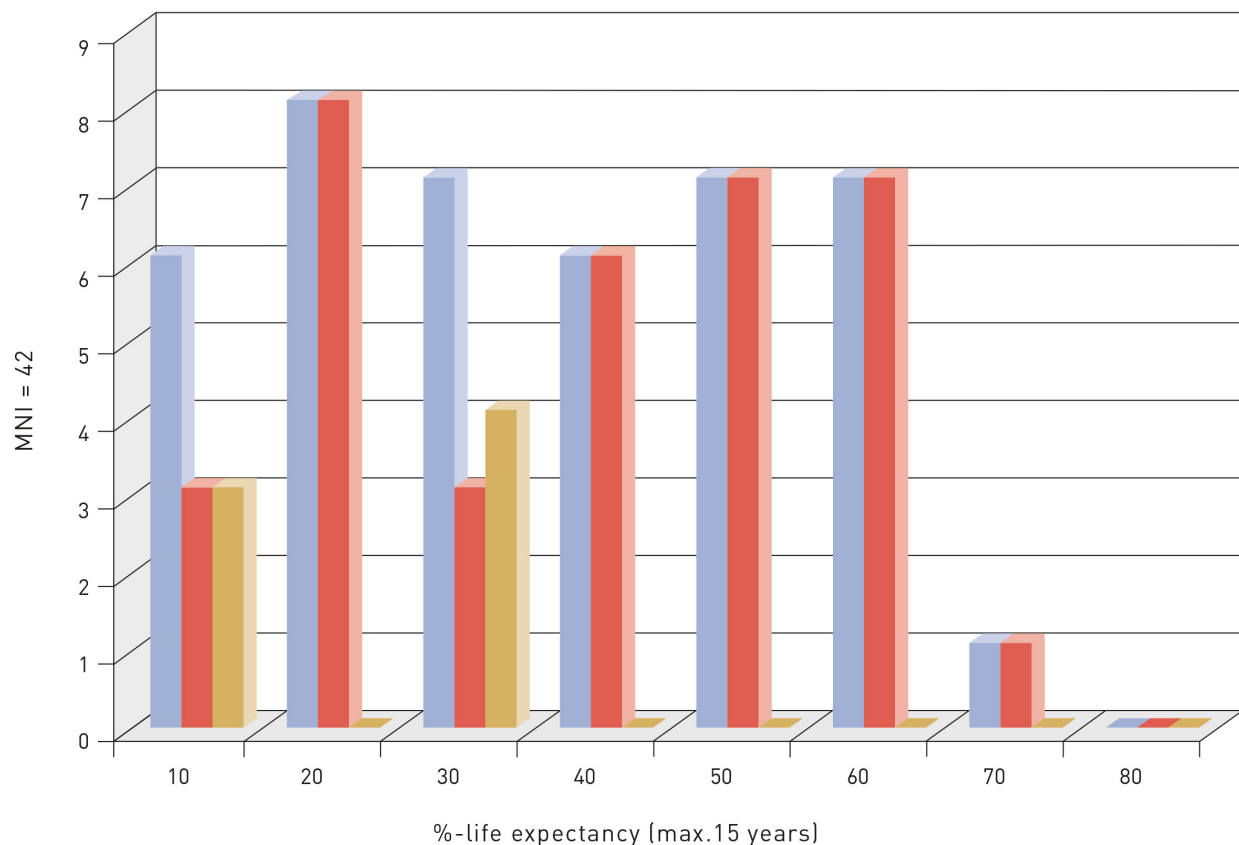


Figure 4 Age distribution of *Dama dama geiselana*, unit 7, for males (red), females (brown), and total (blue). Based on the exact age of death of 42 individuals. Maximum life expectancy for *Dama dama geiselana* was assessed at 15 years²¹. MNI = Minimum Number of Individuals

ther 8 individuals (5.9%) from this unit could only be attributed to family level.

2.3.2 Sex and age

The overwhelming majority (81.6%) of the assemblage could be attributed to sex (**Table 2**). Red deer and fallow deer show similar male/female proportions (*Cervus elaphus* – males: 89.5%, females: 10.5%; *Dama dama geiselana* – males: 90.2%, females: 9.8%) with a dominance of adult males (*Cervus elaphus* – adult males: 76.5%, juvenile/subadult females: 23.5%; *Dama dama geiselana* – adult males: 78.3%, juvenile/subadult females: 21.7%). The assemblage furthermore contains mainly juvenile/subadult females (*Cervus elaphus* – adult females: 0%, juvenile/subadult females: 100%; *Dama dama geiselana* – adult females: 22.2%, juvenile/subadult females: 77.8%).

The analysis of the age distribution undertaken for the cervid assemblage from unit 7 provided results for a MNI of 92 (67.6%). For these individuals the exact age at death could be determined and/or they could be attributed to age-cohort (juvenile/subadult, adult, old). As for *Dama dama geiselana* the exact age at death could be determined for 42 individuals, as opposed to only 7 individuals for *Cervus elaphus*, analysis of the mortality structure focused on *Dama dama geiselana* (**Figure 4**).

For *Dama dama geiselana* all age classes up to 60% of life expectancy are represented in similar frequencies (**Figure 4**), with a noticeable absence of old individuals, i.e. individuals representing 70% of the life expectancy and older. This distribution pattern is also reflected in the assemblage of individuals that did not allow detailed, one-year resolution, age assessments. This includes 40 adult males and two adult females (approx. 40-60% in **Figure 4**) as well

Individual	Age (months)	Sex	SUMMER			AUTUMN			WINTER			SPRING		
			June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
88:4,1-59	14	m												
87:300	14-15	w												
97:14194	15	m												
97:14155	24	m												
97:14202	4	w												
97:14161	18	w												
97:14154	18	m												
87:14151	22	m												
97:14198	>24	m												
97:14150.1	10-12	w												

Figure 5 Season and age of death in months for the cervid assemblage from Unit 7, based on dentition (MNI=10). Birthing season modelled to begin end of June.

as 3 sub-adult males. Together they clearly form a prime-age, catastrophic mortality profile.

2.3.3 Season of death

Season of death could be determined using tooth eruption and wear data from eight juvenile/subadult *Dama dama geiselana* and two *Cervus elaphus* individuals (**Figure 5**). Male and female juvenile individuals of both cervid species died in spring, summer and autumn. For 58 adult *Dama dama geiselana* males whose antlers survived more or less complete, it was possible to determine season of death based on the state of antler regeneration. According to this evidence adult males died only in autumn, an observation already made by Pfeiffer and Mania for the assemblage unearthed up to 1996^{3,17}.

2.3.4 Bone surface modifications

The bones from NN1 were discovered during mining activities and many skeletons suffered recent damage. These damages can easily be identified and distinguished from green bone damage due to their white colour and their irregular fracture planes that resulted from the breakage of the already fossilized bone. Most of the modern breaks could be conjoined as many skeletons were recovered *in toto*. The pelvis of a *Dama dama geiselana* clearly illus-

trates such modern damage (**Figure 10**), though it can be clearly distinguished from a *perforation* found on the same specimen (see further section 2.3.7).

Apart from recent damage, the cervid bones from NN1 are excellently preserved and traces of weathering (cf.²⁰) could not be observed. However, some individuals showed a random papyraceous micro-exfoliation of the outermost bone surface (**Figure 6**). As this micro-exfoliation was not observed during or directly after excavation², it is most likely linked to post-excavational drying of the skeletal elements. The survival of the very fine cut-marks observed on bones from NN1 (**Figure 7**) may be related to the degree of bone-drying, whereas the more invasive traces of other agents (i.e. carnivore marks) would not have been affected.

2.3.5 Carnivore modifications

The remains of 11 individuals (*Dama dama geiselana*: n=9, *Cervus elaphus*: n=2) bear traces of carnivore modification (8.1% of MNI). Protruding portions of the skeletons such as proximal ulnae, *tuber calcanei* of the calcaneus, pelvis and proximal tibia show tooth marks and traces of gnawing (**Figure 8**). Adult male and female individuals of *Cervus elaphus*, and adult males (n=6), juvenile males (n=1) as well as an adult and a juvenile female of *Dama*



Figure 6 Micro-exfoliation of the outermost bone surface observed on the femur (left) and the metatarsus (right) of resp. fallow deer individual 88:10 and in detail (lower-left, lower-right). This micro-exfoliation is most likely related to post-excavational drying.

dama geiselana had been gnawed. Although the size of the tooth marks does not necessarily provide information on the agent²², the damage observed on the bones points to a small sized carnivore (e.g. **Figure 8**). Hyenas as bone modifying agents can,

however, not be excluded as shown by gnawing traces on an isolated antler fragment¹⁷. The presence of hyenas is also documented by a coprolite²³.

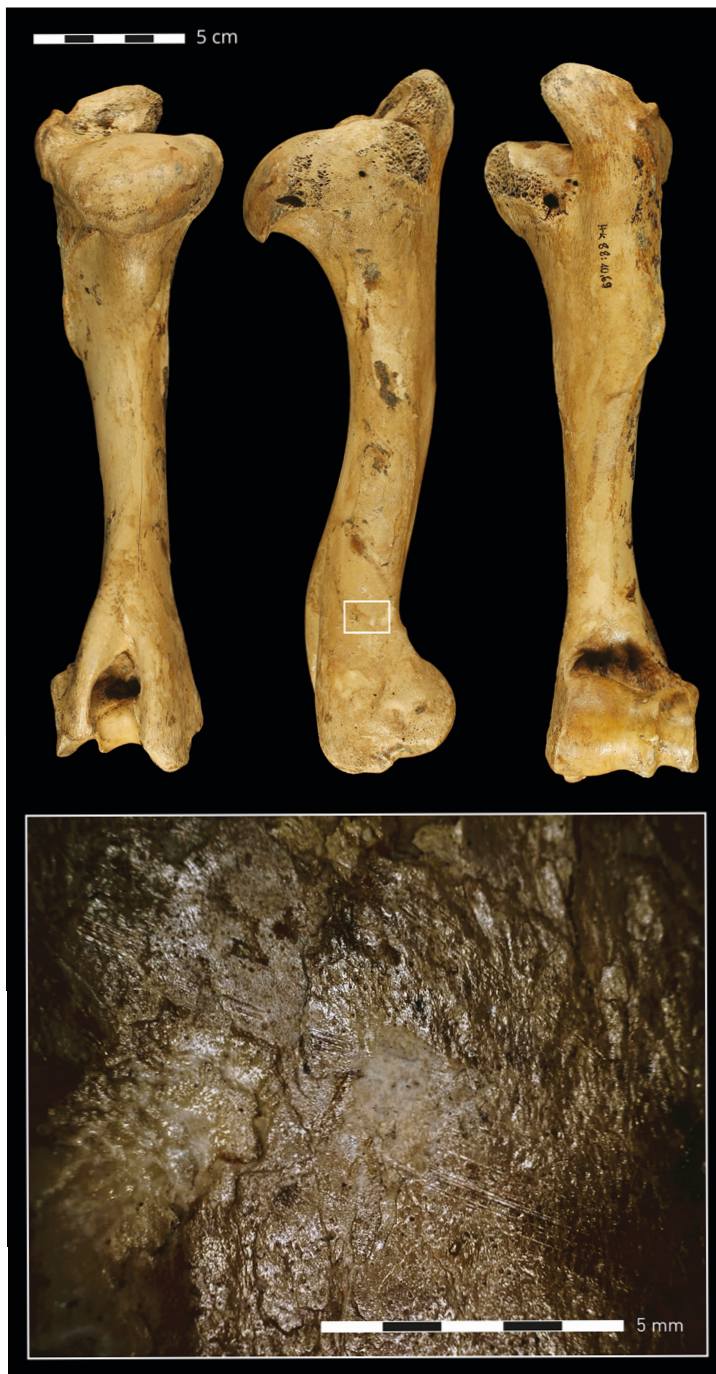


Figure 7 Very fine cut-marks, observed on the outermost layer of the humerus of fallow deer individual 88:10, where the bone has not been altered by micro-exfoliation of the surface.

2.3.6 Cut-marks

Cut-marks were observed on seven individuals (5.1% of MNI): four adult *Dama dama geiselana*, two *Cervus elaphus* and one juvenile *Cervus* sp. (Table 3; e.g. Figure 9). Cut-marks have been observed on subadults (MNI=2) and on adult males (MNI=5). The marks are mainly located on the dia-

physes of meat bearing long-bones, pointing to the defleshing of at least parts of the carcasses (Figure 9). Cut-marks were not observed on skeletal elements with low meat content i.e. metacarpi and metatarsi, phalanges, radii and ulnae. Cut-marks on the spines of thoracic vertebrae point to at least partial skinning and filleting. Cut marks indicating the separation of ligaments – usually located on the

epiphyses of long bones – were not observed, in accordance with the *in-situ* recovery of complete articulated carcasses. Given the observed microexfoliation of the bones (Figures 6, 7), and the meat-focussed carcass-exploitation pattern, the number of cut-marked carcasses cannot be taken as a direct measure for the extent to which hominins exploited cervids at NN1.

2.3.7 Perforations

Round *perforations* have been observed on bones from two fallow deer skeletons. The first individual, no. 97:14159, represents an adult 6-7 year old male which died in autumn, judging from its antler development. The complete skeleton of this buck was found in articulation lying on its left side (Figure 1

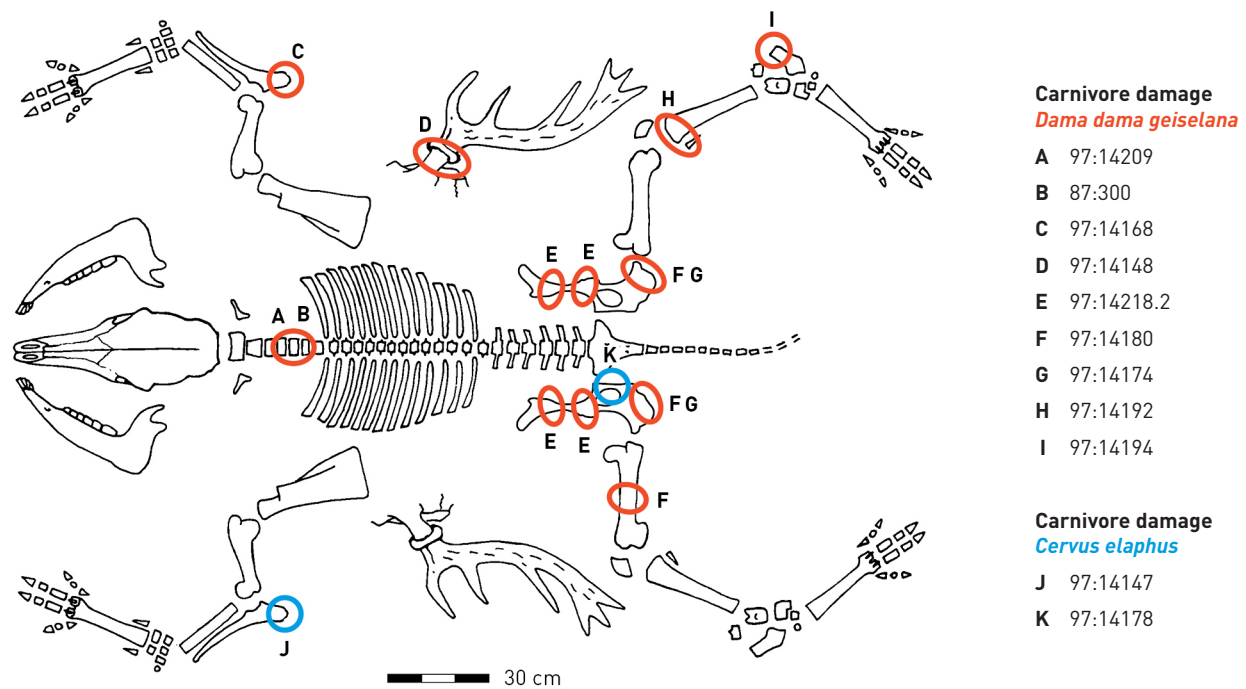


Figure 8 Cervid assemblage, unit 7. Location and orientation of carnivore modifications. A-K= inventory numbers for Cervid skeletons (top). Tooth marks (ca. 5-6 mm in diameter, i.e. half the size of the *perforations* (section 2.3.7.) observed) by a small-sized carnivore on the cervical spine of the still articulated *Dama dama geiselana*- individual no. 87:300 (B) (bottom). The head of the juvenile doe was bitten off at the 4th vertebra and rested displaced between its front legs³.

Table 3 Counts of Minimum Numbers of Individuals (MNI) with cut-marks and/or perforations in the cervid assemblage, unit 7.

	<i>Cervus elaphus</i>	<i>Dama dama geiselana</i>	<i>Cervus</i> sp.
Cut-marked	2	4	1
Perforations	0	2	0

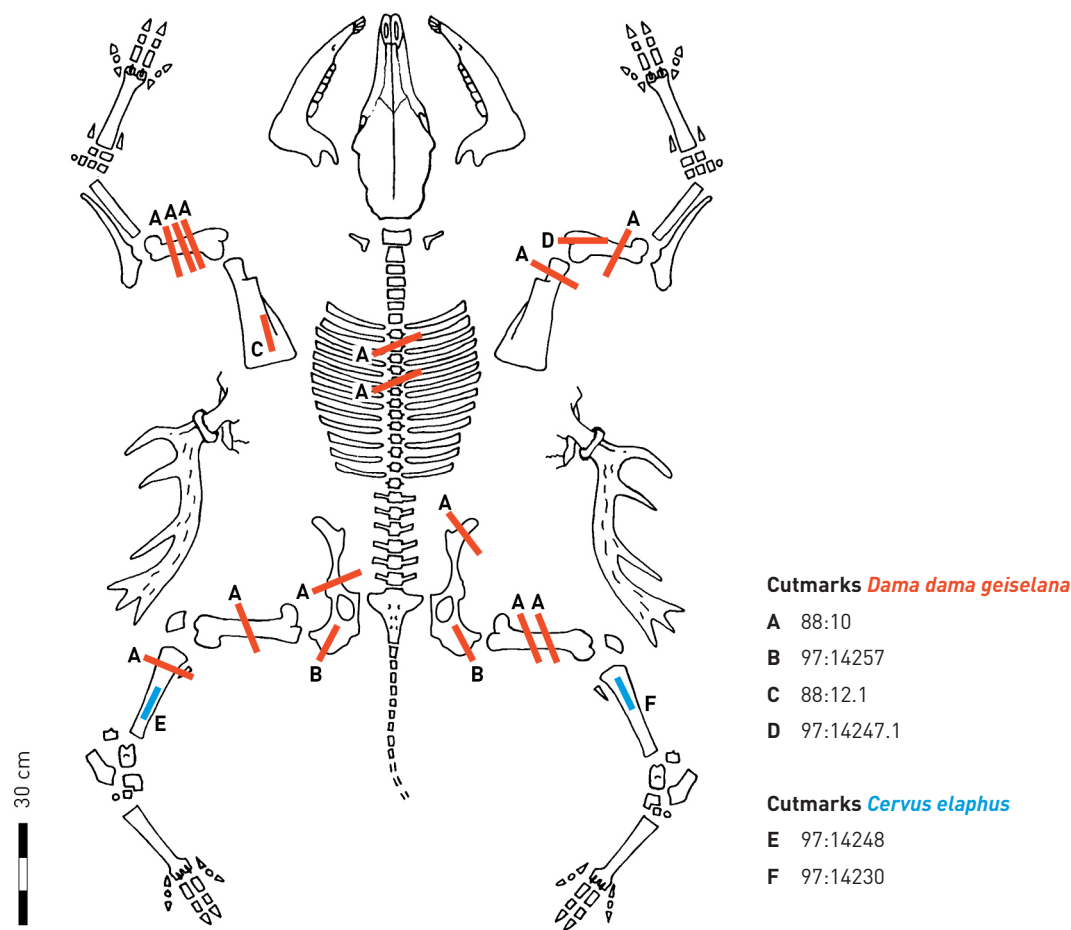


Figure 9 Cervid assemblage, unit 7. Location and orientation of cut-marks. A-F = inventory numbers for cervid skeletons

main text). The cervical spine showed a dorsal curvature. The forelegs were parallel to each other and the hind legs were bent.

The *perforation* is located on the *Facies glutea* of the *Ala ossis ilii* of the left part of the pelvis, next to the spine. It measures 11 mm in diameter. The *perforation* shows characteristics of an entry-wound on the lateral face of the pelvis. Towards its caudal edge, the rim of the *perforation* is marked by multiple circular fractures with splintered bone-com-

pacta, fragments of which have been pushed into the conical channel of the wound. On the cranial edge, the single circular fracture rim is characterised by a marked *protrusion*.

The medial face of the *perforation* shows all the characteristics of an exit wound. The rim of the *perforation* is clearly defined on the cranial edge and is accompanied by splintering of the immediately adjacent bone compacta. The caudal part of the *perforation* is characterised by a partially detached

bone flake and has a convex rim (**Figure 10**; Figure 2 main text; Supplementary Model).

A second *perforation* was observed on the right plate-shaped broadening (*Lamina ventralis*) of the *Processus transversus* of the 6th cervical vertebra of an adult, 6-7 year old, male fallow deer (no. 88:10, **Figure 11**). The articulated skeleton of this individual (Figure 3 main text) was complete, except for the head which had been severed during mining activities. The buck was lying on its left side. The cervical spine was bent dorsally parallel to the thorax. The thorax itself is curved upwards, and the right fore leg superimposes the hind legs. Numerous cut-marks have been detected on the bones of this buck (Figure 3 main text; **Figure 9**).

The oval *perforation* has a maximum diameter of 11 mm. The opening has a regular, serrated rim, and

a *protrusion* on the ventral/cranial side. A fine crack extends caudally from the *perforation*.

2.4 Discussion

2.4.1 Assemblage composition

The cervid skeletons primarily belong to adult male individuals that had died during the rutting season, when the male-herd structure breaks up and adult males become solitary²¹. The age structure of the cervid assemblage indicates a catastrophic, prime-age mortality with an absence of senile individuals. Females and subadults are underrepresented and in contrast to the males, died throughout the year except during winter. Taking into account the seasonal



Figure 10 *Perforation* on the pelvis of a male *Dama dama geiselana* (No. 97:14159), seen from the lateral (below) and medial (above) sides; the inset shows a detail of the *perforation* from the medial (left) and lateral (right) sides of the pelvis

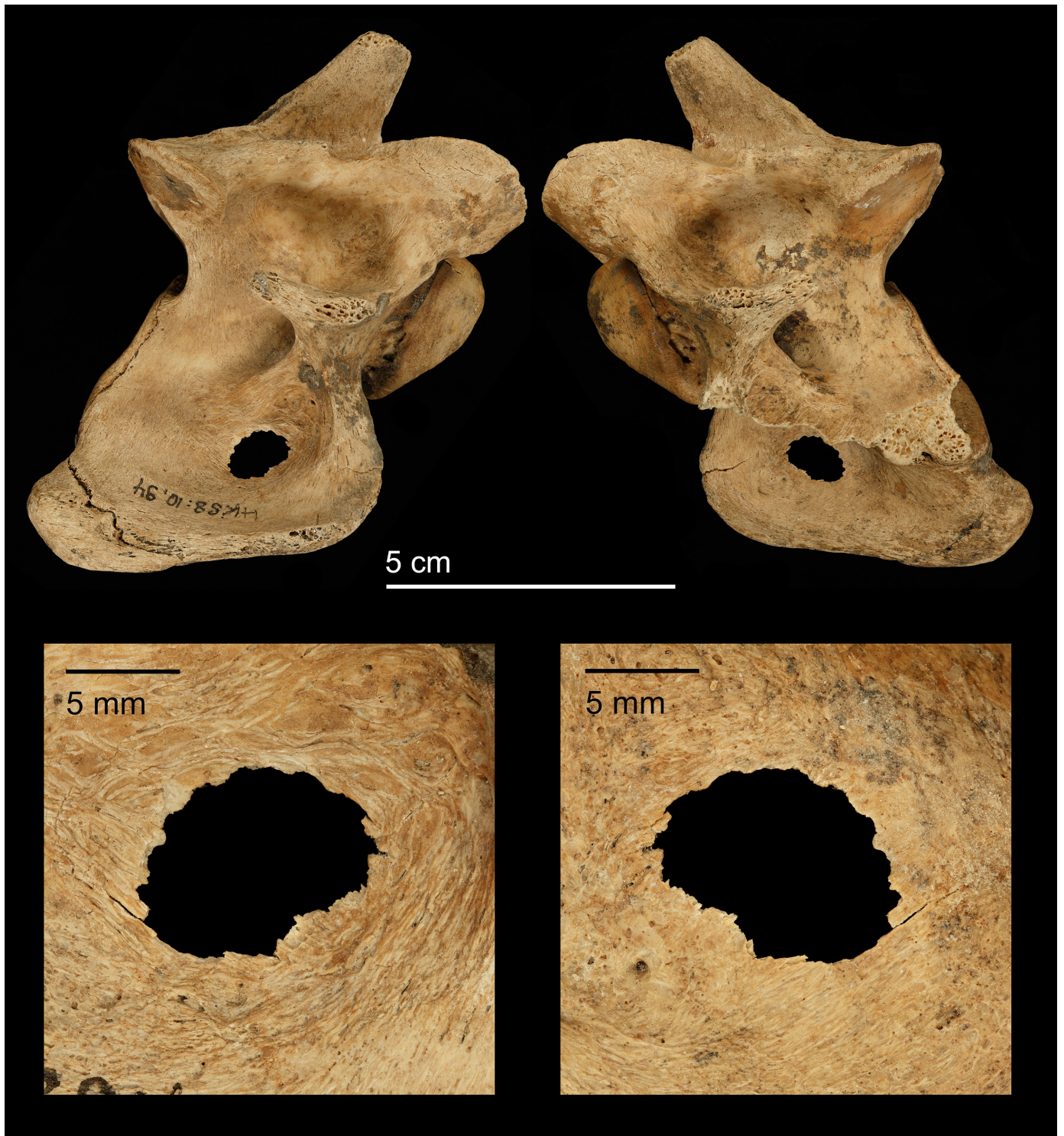


Figure 11 Perforation on the 6th cervical vertebra of a male *Dama dama geiselana* (No. 88:10) from the left and right view; inset showing details of the *perforation* from the lateral (bottom left) and medial (bottom right) side of the transverse process.

data and placing this against the ethological background, the sheer number of adult males suggests a long-term accumulation, an interpretation in accordance with sedimentological observations at the site³.

Studies on cervid mortality after catastrophic floods illustrate the interdependence between animal ethology (i.e. seasonal changes in herd structure regarding sex and age) and the composition of a death assemblage²⁴. Pfeiffer interpreted the age-structure of the NN1 cervids as the result of repeated catastrophic mass death events caused by poisoning of the standing water due to cyanobacterial bloom in autumn¹⁷.

However, several aspects of the assemblage and its sedimentary context are not in accordance with repeated, seasonal death of animals by poisoning. The results of the biochemical analyses indicate that pigments characteristic for cyanobacteria are preserved in the sediment, but could not directly demonstrate toxicity²⁵. Corpses in standing water are characterised by a passive body posture without the dorsal curvature of the spine²⁶. Pfeiffer suggested that the large antlers of the males anchored the corpses under water, resulting in carcass distortion. As the curvature of the spine, indicative of dry conditions, is regularly observed in females and juveniles without antlers and subadults with small antlers, this hypothesis has to be rejected. In the light of the cut-marks, as well as the carnivore and rodent damage identified in this study, the argument that a lack of surface modifications can be the result of carnivores, rodents, and hominins rejecting the carcasses as a food source due to poisoning by cyanobacterial bloom¹⁷, has to be dismissed as well.

Moreover, given the purportedly repeated occurrence of these events, a broader range of large mammalian taxa should be expected, as is documented at other *Lagerstätten*²⁷. Apart from the cervid skeletons, the archaeological evidence from unit 7 only consists of an almost complete carcass of a large bovine, and the fragment of a bovine pelvis together with skeletal remains of *Elephas (Palaeoloxodon) antiquus*. They represent the scattered remains

of more or less complete carcasses of four adults and a juvenile.

Finally, we would also expect to find the regular presence of old individuals, and that year-round mortality had produced a more balanced ratio between male and female individuals, without the peak in mortality during the rutting season that had primarily affected prime adult males.

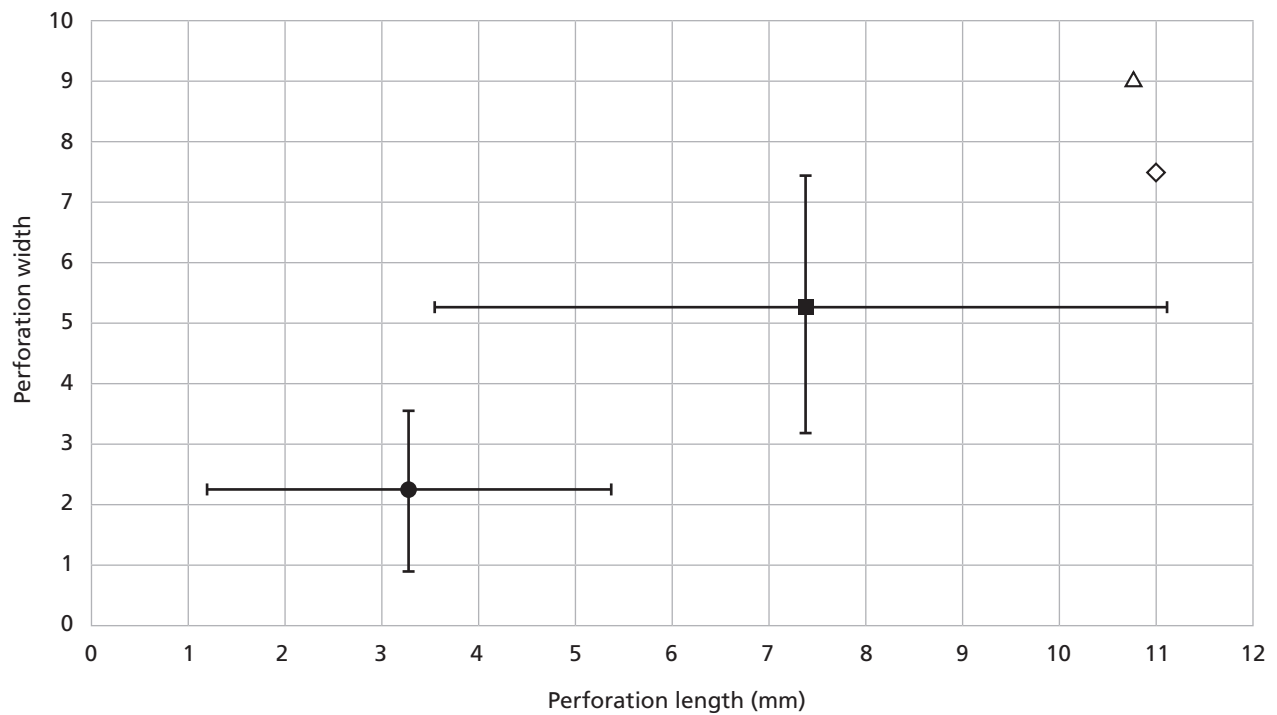
2.4.2 Deposition context and burial

Several arguments indicate that the cervid remains from NN1 accumulated on dry land during necrobiosis, where hominins and carnivores had access to them. Most of the cervid skeletons were characterized by a dorsal curvature of the spine, resulting from desiccation of the neck muscles, a phenomenon usually observed in arid or semiarid environments²⁶. The burial of the carcasses must have taken place very quickly in order to ensure their preservation as complete, articulated skeletons. In addition, the remains lack traces of climatically induced weathering, typical of bones left exposed to the elements over a period of time. Furthermore, hominins and carnivores appear to have had access to and exploited the carcasses, as evidenced by the presence of respectively cut-marks and carnivore marks, as well as access by rodents as evident from occasional traces of gnawing on the bones.

2.4.3 Perforations and potential non-anthropogenic agents

Unlike the tooth- and cut-marks identified in this study, the agent(s) producing the observed *perforations* is (are) not directly identifiable. A variety of natural agents can produce *perforations* in bones. Biotic agents which might have produced the *perforations* are necrophilous entomofauna, carnivores, vultures, deer and hominins.

Necrophilous entomofauna, such as beetles of the genus *Dermestes*, can produce holes into bones comparable in size to the *perforations* observed on NN1, for use as pupation chambers. The beetles produce funnel-shaped holes with irregular, circular



■ Hyaena bite marks-epiphyses* ● Hyaena bite marks-diaphyses* △ Perforation NN1 pelvis ◇ Perforation NN1 vertebra

Figure 12 Plot of the size of the two NN1 *perforations* in relation to the known dimensions of hyaena bite marks on epiphyses and diaphyses as published by Domínguez-Rodrigo and Piqueras³²

margins^{19,28}, whose morphology differs considerably from that of the NN1 *perforations*.

Cone-shaped and inverted-cone shaped *perforations*, in particular, can be produced by single cusped teeth of carnivores. The morphology of these *perforations* is highly variable, depending on the taxa involved^{19,29,30}. The NN1 *perforations* observed are too large (Figure 12, see also ref.³⁰: Figure 10) and too roundish to have been produced by the fangs of an hyena, the largest potential bone-perforating predator in NN1. Furthermore, the pelvis perforation displays *multiple circumferential cracks* with bone fragments pressed into the conical wound channel, which is different from carnivore modifications. Moreover, the *perforation* of bones due to carnivores ravaging of complete or partially complete carcasses is always accompanied by additional traces of gnawing, puncture marks and/or other *perforations*¹⁹. The two perforated NN1 carcasses do not show any traces of carnivore interference. NN1 carcasses with traces of carnivore involvement

always show a number of such traces, e.g. a carcass with tooth marks observed on the cervical spine of a subadult female fallow deer from unit 7 (Figure 8).

Vultures leave *perforations* comparable in size to the damages observed on the finds from NN1³¹, but the irregular shape of the former distinguishes them from the marks discussed here.

Finally, during fights in the rutting season, the antler of cervids can cause injuries primarily located on the forepart of the animal; scarring of the haunches is rarely observed and injuries are mostly fleshwounds^{33,34}. Rupturing of the stomach and ensuing peritonitis resulting from the opening of the abdomen has been reported (cf.³⁵), but *perforations* of bone have not been observed so far. The impact angle of the 97:14159 find (Supplementary Information Section 3) is also very difficult if not impossible to reconcile with a “rut fight” interpretation.

The specific morphology of the two lesions as well as their locations strongly suggest that spear

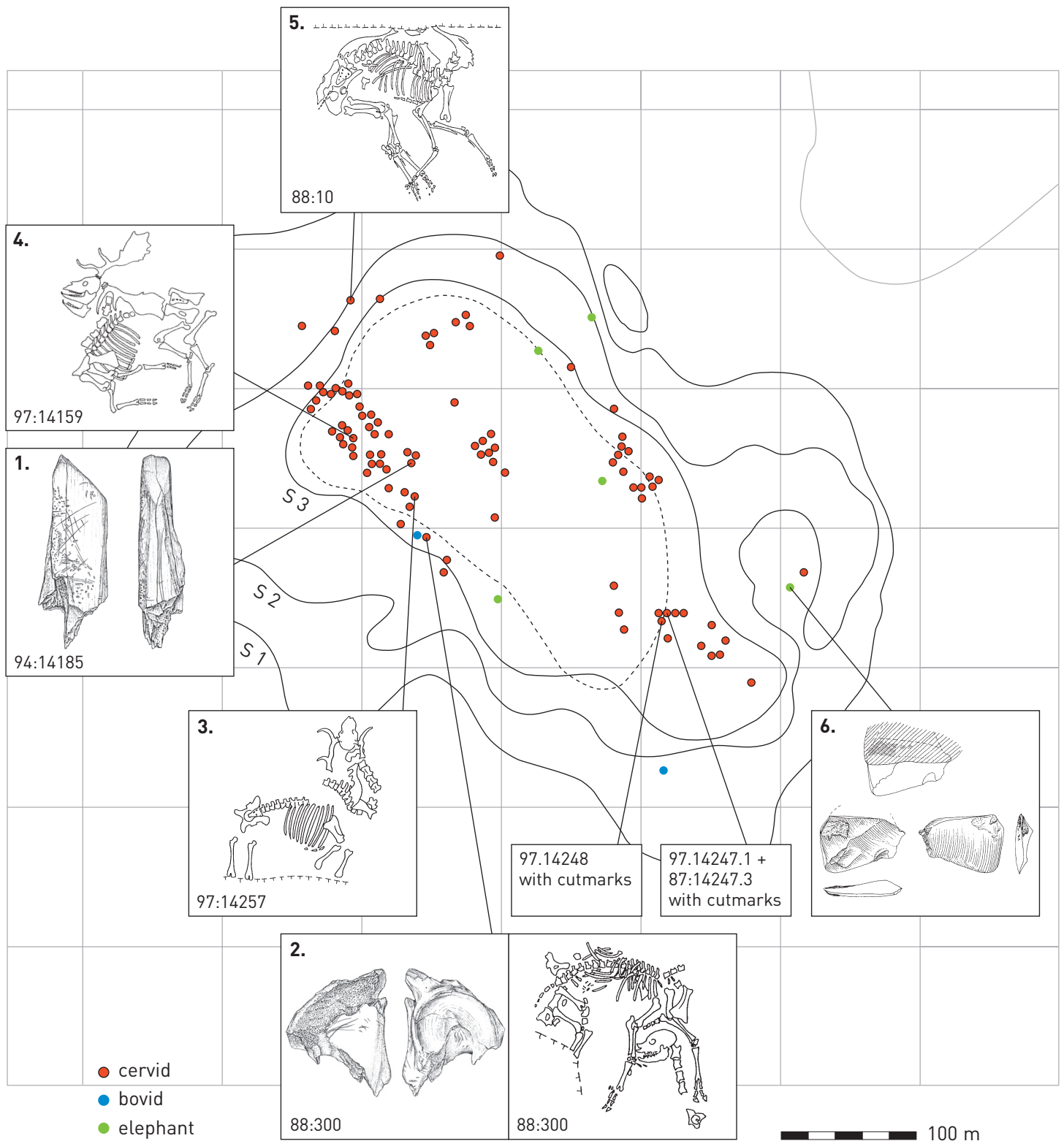


Figure 13 Unit 7, Distribution of cervids ($n=96$) for which spatial data is available, as well as large bovine and elephant-remains. 1. Bone tool found together with Individual No. 94:14185, 2. Cut-marked pelvis of large bovine associated with Individual No. 88:300, 3. Individual No. 97:14257 with cut-marks, 4. Individual No. 97:14159 with *perforation*, 5. Individual No. 88:10 with *perforation*. 6. Flake with oak residue associated with *Elephas (P.) antiquus* remains. Spatial data taken from²³

using hominins were the agents responsible for the observed *perforations*, a hypothesis that has been evaluated in a series of dedicated ballistic experiments, reported in section 3 of this Supplementary Information.

2.4.4 The role of hominins in the formation of the NN1 cervid assemblage

Direct interaction between hominins and cervid carcasses at NN1 is clear, as demonstrated by cut-marks that indicate partial defleshing. The character of the assemblage, with a dominance of male, adult fallow deer that died in autumn, which is maintained throughout the unit 7 deposits, best fits with a recurrent seasonal exploitation strategy taking place during this season. This choice of season may have been to profit from the optimal physical condition and body mass of bucks during the rutting season (from late September to late November³⁶). The pattern of individuals killed in autumn is augmented with those that were killed all-year round, as evidenced by the juvenile/subadult individuals that died all-year round (see **Figure 5**). The cut-marks indicate first and exclusive access by hominins, as cervid individuals displaying cut-marks and individuals gnawed by carnivores are mutually exclusive.

Other finds from the cervid-bearing deposits also attest to the presence of hominins in the immediate area, both within the NN1 deposits (**Figure 13**) as well as from the neighbouring NN2 basin (find level NN2/1a, see **Figure 3**)^{23,37}. At NN1 these finds include a flint flake, uncovered in association with an elephant carcass, bearing an organic residue. Biochemical analysis showed the substance to be comminuted bark of oak, interpreted to have been used for the tanning of fur³⁷. Further indications for the presence of hominins include a bone fragment with rounded fracture edges, numerous cut-marks and areas of use-wear, typical for bones which were used as polishing tools and bones used for retouching lithic artefacts. The fragmented and cut-marked remains of a large bovine pelvis further demonstrate hominin presence at the NN1 location, together with the NN2 record providing unambiguous evi-

dence for a hominin presence in the extended Neumark-Nord landscape during the middle part of the Eemian Interglacial.

3 BALLISTIC STUDIES

3.1 Introduction

Here we describe experimental ballistic¹ studies aimed to test the hypothesis that the *perforations* found on the bones of fallow deer individuals mentioned above (section 2.4.3) were caused by hominins, and furthermore to establish the exact processes by which these *perforations* were formed.

3.2 Material and methods

3.2.1 Experimental setup

TARGET

In order to warrant replicability (see³⁸), have better control of the variables at stake, and allowing immediate monitoring of lesion formation during the experiment, individual bone skeletal elements were used, rather than complete carcasses or body parts, where the bones are embedded in organic tissue. Twenty-four bone targets (i.e. samples) were prepared using 14 pelvises and 10 scapulae with intact periost, obtained from hunted German red deer (*Cervus elaphus*). The bones had been frozen and were defrosted before use. Because European extant *Dama dama* is 15-20% smaller than the Pleistocene subspecies *Dama dama geiselana* encountered at NN1³⁹, red deer is more similar to the latter in terms of size and is therefore used in the experiments (Figure 14). Ten scapulae were included in the analysis to study the variability in lesion morphology in general and on other flat bones with a lower thickness in particular.

To ensure comparability of results, the bones for the targets were cut to prepare samples of equal size that fit into the plastic mould (100 x 150 mm) used

for producing the blocks of ballistic gelatine. Therefore, the *os ilium* was cut at its *ramus* as well as at its dorsal part in order to remove the *ilium corpus* and *tuber sacrale* (Figure 15). Of the scapulae only the proximal 1/3 of the blade was used. All bones were horizontally positioned with the lateral face upwards and fully embedded in ballistic gelatine (pig, 240 Type A; 20% solution) and were stored at 3 °C. The bones were embedded in gelatine for two reasons: a) to create a homogenous and binding environment holding the hard target materials, also when fragmented after impact; b) to observe wound formation not only in hard tissues, but also in the soft tissues that normally surround them. The gelatine coverage on the initial impact side was standardized to a thickness of 20 mm.

The targets were secured in a frame of rigid foam, which was fixed to a wooden board. This setup was attached to an upright standing working bench (mass of 80 kg) when thrusting took place in horizontal direction. For vertical thrusting, the frame was detached and positioned on the floor. The experiments were carried out at room temperature (18 °C).

THRUSTING SPEAR DESIGN

The spear used for the experiments consists of three core components: an aluminium shaft, sensors and a wooden tip. The wooden tip (angle of convergence = 17° and shaft diameter = 30 mm) was modelled, in terms of size, shape and physical properties, after the spear found at Lehringen, because of its Last Interglacial age and its inferred use as a thrusting weapon⁴¹. As the tree of the wood used for the Lehringen spear, yew (*Taxus baccata*) is a protected species under German law⁴², wood from the beech (*Fagus sylvatica*) was used ('B'), which has a comparable compressive strength as yew ('Y'):

$$\sigma_{DY} = 56 \frac{N}{mm^2} \quad \sigma_{DB} = 64 \frac{N}{mm^2}$$

¹ Although ballistics describe in a strict sense the behavior of projectiles and targets, we still opted to use this term for our thrusting spear experiments that also include transference of mass of the user, because of its familiarity to the reader and the fact that it covers not only the movement (e.g. as in kinematics), but also the effect on the materials it comes into contact with.

⁴² http://www.gesetze-im-internet.de/bartschv_2005/anlage_1.html

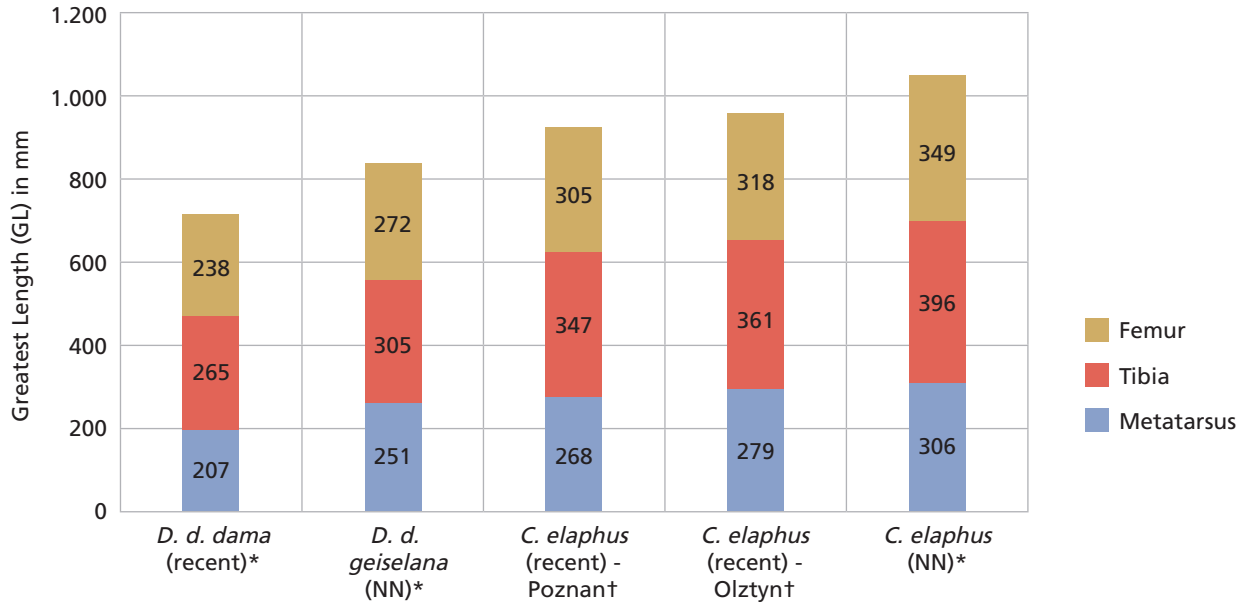


Figure 14 Greatest length (GL) of femur, tibia, metatarsus and greatest total length hind leg of indicated populations, averaged between males and females, adults only. Note that the difference between recent *D. d. dama* and *D. d. geiselana* is larger than between recent *C. elaphus* and *D. d. geiselana*. *Metatarsus length cf.¹⁷ and proportions femur/tibia/metatarsus cf.³⁹, femur length cf.⁴⁰, proportions femur/tibia/metatarsus cf.³⁹.

In our study plastic deformation of the wood appeared as dulling of the tip. The degree of dulling can be described by the surface area of the tip after the deformation (**Figure 16**). In order to estimate the degree of dulling one could expect for a wooden tip of the same shape made out of yew, we compared both wood types using the following formula for compressive strength:

$$\sigma_D = \frac{F}{A}$$

where F is the force applied in longitudinal direction, and A is the area in contact with the target after dulling. Taking the ratio between both material constants and reformulating results in

$$A_B = \frac{\sigma_{DY}}{\sigma_{DB}} A_Y = 0.87 A_Y$$

This means that the area in contact with the target during the impact event using wood from yew can be about 1.15 times larger compared to wood from beech assuming otherwise the same conditions. Even though this estimate uses conservative numbers for the material properties of wood (e.g. with regard to humidity), this comparison shows that the

mechanical properties of a yew-tipped spear do not considerably differ from a beech-tipped spear at the impact event, and therefore do not influence lesion formation.

The shaft consisted of two aluminium tubes connected by a clamp serving as a haft. A second clamp at the head of the spear served as a holder for the wooden tip, which allowed replacement (**Figure 15**). Between the tubes and the tip holder a custom, 3D printed sensor mount with an Inertial Measurement Unit (IMU: Xsens MTi 100), a camera (PointGrey Blackfly: BFLY-PGE-13E4M-CS), and a 6 axis Forces and Torques (F/T) sensor (ATI Omega 80) were integrated. The sensor mount was designed to align and protect the delicate sensors while withstanding rough usage.

The spear has a length of 180 cm (excluding the 30 cm long wooden tip) and, due to the measuring equipment and protective casing, a total mass of 3.13 kg. Although certainly heavier than that of Lehringen or other thrusting spears known from the archaeological and ethnographic records (e.g. 772 ± 358 g; 776 ± 388 g⁴²), the effect of its mass on the experiment should be less relevant due to the overall lower influence of mass on kinetic energy

compared to velocity ($E_{kin} = \frac{1}{2} m v^2$), and, when used in a thrusting motion, due to the transference of mass into the spear by its user⁴³⁻⁴⁵. The validity of the latter will be further explored based on the ballistic data obtained from this study.

3.2.2 Participants and experimental procedure

All three male participants were experienced in handling thrusting weapons. Two of three can be described as trained in terms of their overall physical shape, and both individuals have advanced skills in martial arts by holding Kung-Fu brown and black belts and practicing minimally twice per week for 90 minutes. Experiments performed by these individuals are indicated by 'KF'. The untrained participant is well-experienced in the use of prehistoric weapons and is indicated by 'LGM'.

The thrusts were performed in horizontal (parallel to the ground) and vertical (head to toe) mode (**Figure 15**). In order to get accustomed to the thrusting spear, test runs were performed in horizontal mode. For the horizontal thrusting the target height was adjusted to the waist height of the participant. The participants were not instructed in the use of the weapon, including the starting position and the handling of the spear. Each attempt was filmed and the target was photographed both before and after the removal of the spear.

After each impact, the wooden spear tip was inspected for damage. When damaged, the tip was removed and the damage documented. In total five spear tips were used and exchanged when needed. The tips were given a standardized shape and were maintained by sharpening, using a sharpening-head extension for drilling machines. The targets were re-

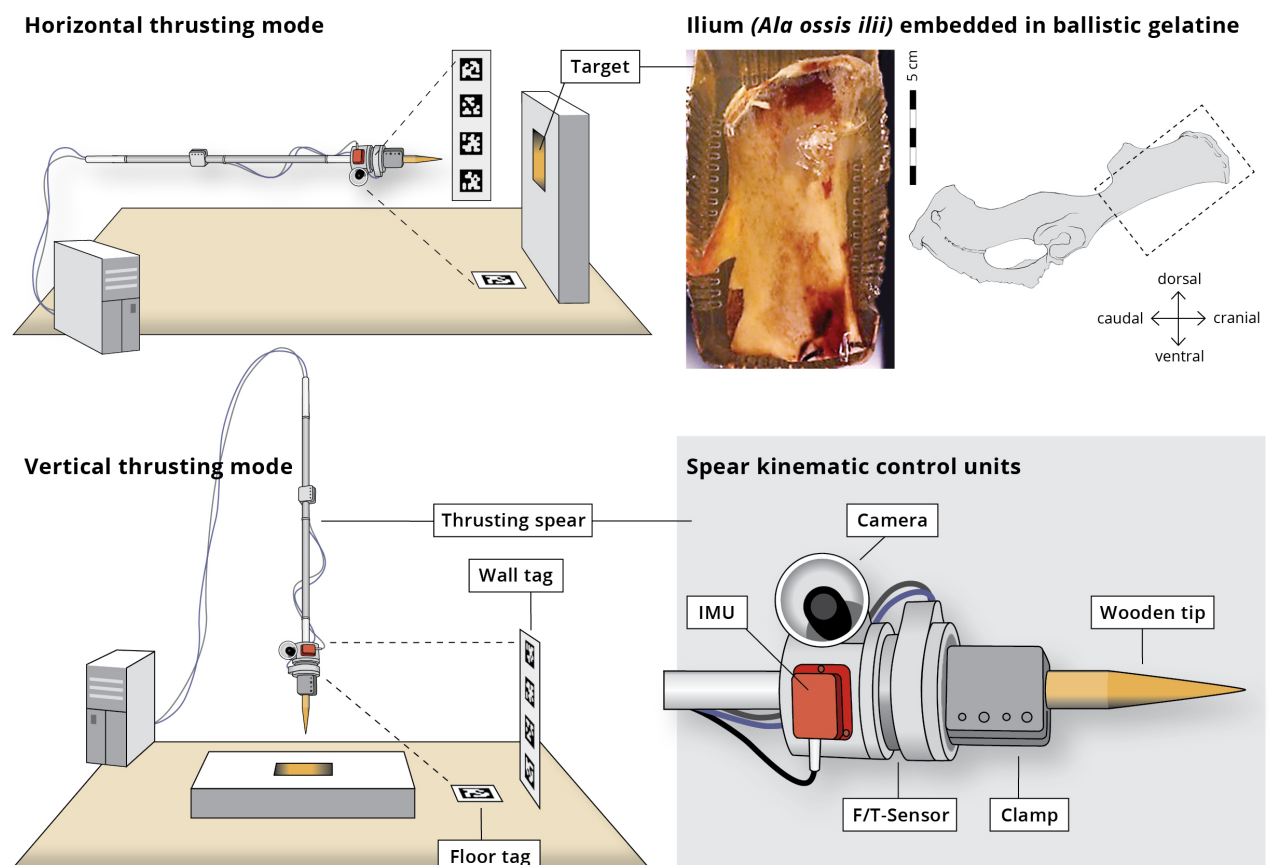


Figure 15 Experimental setup for horizontal and vertical thrusting experiments; top and bottom left: spear with sensors connected to a computer and position of spatial reference markers; top right: pelvis target embedded in gelatine; bottom right: spear-head, sensors and clamp for replacing the wooden tip.

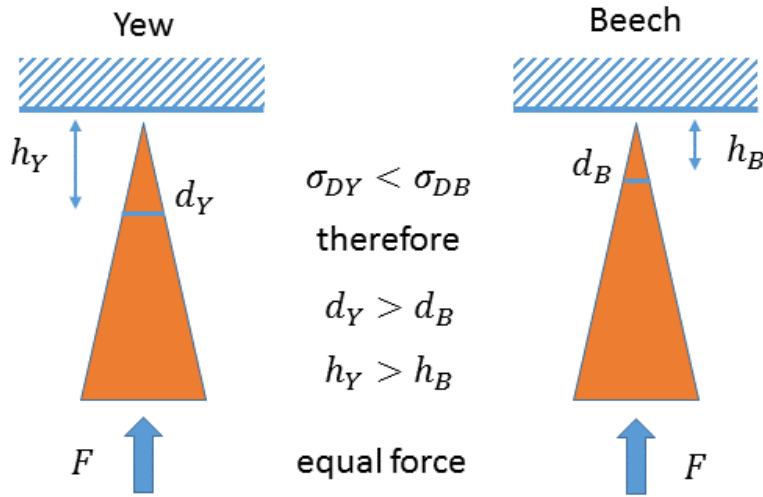


Figure 16 Illustration of the relationship between compressive strength (σ_d), force (F), surface area of the compressed tip (A), and the crushing depth (h) for the conic wooden tip of beech (B) and yew (Y) after deformation. Because the compressive strength of beech is higher than that of yew, the amount of compression for beech is lower.

used if the gelatine remained intact after an experimental run and replaced when the gelatine bed was disintegrating or when the bone within the target was damaged. The scapulae targets could only be used once, as all of them were damaged with the first strike. In total 41 thrusting experiments were undertaken. Of these 31 were performed on the 14 pelvis targets (bone pelvis = BP) and 10 experiments on the 10 scapula targets (bone scapula= BS).

3.2.3 Spear data acquisition and data processing

DATA ACQUISITION

The measurement set-up of the spear allows to independently measure linear acceleration and angular velocity (IMU), forces and torques (F/T sensor), as well as position and orientation (estimates from camera and IMU), which were sampled at 200, 100 and 20/200 Hz respectively. The camera was operated at a resolution of 640 x 512 pixels. The F/T sensor readings were sampled using a National Instruments PCI-6220 M 16-bit DAQ card. Assuming rigid body dynamics, the resulting data describes the spear trajectory, including external forces and torques applied to it at high resolution.

For estimation of position and orientation the visual-inertial motion capture system RCARS was used⁴⁶, running on a standard PC using Linux Ubuntu 14.04 as operating system with ROS Jade (Robot Operating System) installed. RCARS fuses relative pose measurements of the camera at low frequencies with acceleration measurements of the IMU at high frequencies, which results in a drift free pose estimate of the spear. The pose measurements of the camera are based on the recognition of printed landmarks fixed in the experimental environment (Figure 15). Seven of these tags with an edge length of 15 cm were used. They were positioned ca. one meter away from the camera.

DATA PROCESSING

Important processing steps of the raw data are gravity compensation of the IMU measurements, transformation from individual sensor coordinate frames to a common coordinate frame and synchronization of the time axis of each sensor time series.

IMU acceleration measurements by default include a constant offset caused by the earth gravitational acceleration. This offset was compensated for by subtracting a constant vector of 9.81m/sec²

in vertical direction transformed into the coordinate frame of the IMU.

The sensor trajectories are sampled in separate coordinate frames during data acquisition. In the pre-processing step these trajectories are transformed to a common coordinate frame located at the spear tip. All kinetic quantities presented in the results are expressed in this Tip Frame. The transformation between camera and IMU was calibrated by RCARS automatically, whereas the transformations from IMU and Camera to the F/T sensor and to the Tip Frame were taken from the technical drawing of the spear.

Time synchronization was based on automatic identification of the impact event and corresponding shifting of the time axis, such that the timestamps of the impact events coincide for all time-series. For the IMU data and the F/T sensor data the impact appears as a pronounced peak in the time series, which is significantly larger than other potential peaks. The impact event has been defined as the time point at which the derivative exceeds a threshold for the first time. This threshold was set such that it corresponds to the beginning of the peak (**Figure 17**). For the pose estimates the impact event was determined as

the timestamp corresponding to the maximal turning point of the first derivative of the position, i.e. the maximum velocity. The justification to this assumption is that the velocity is nowhere higher than just before the impact.

From the processed time series the relevant kinetic quantities were extracted. Velocity before impact was computed by taking the first derivative of the position trajectory. Peak forces were extracted as the maximum value of the force trajectory. Additionally, the kinetic energy of the spear was computed as:

$$E_{kin} = \frac{1}{2} m v^2$$

where m is the mass of the spear, and v its velocity of the spear tip before impact. This measure is only used for a comparison with work on target (see below).

Since the energy transferred into the target does not only consist of the moving mass of the spear but also of the mass transferred by the participant into the spear during the impact event, we calculated the work applied to the target (*work on target* or W) as:

$$W = \int_{t_{start}}^{t_{end}} F(t) v(t) dt$$

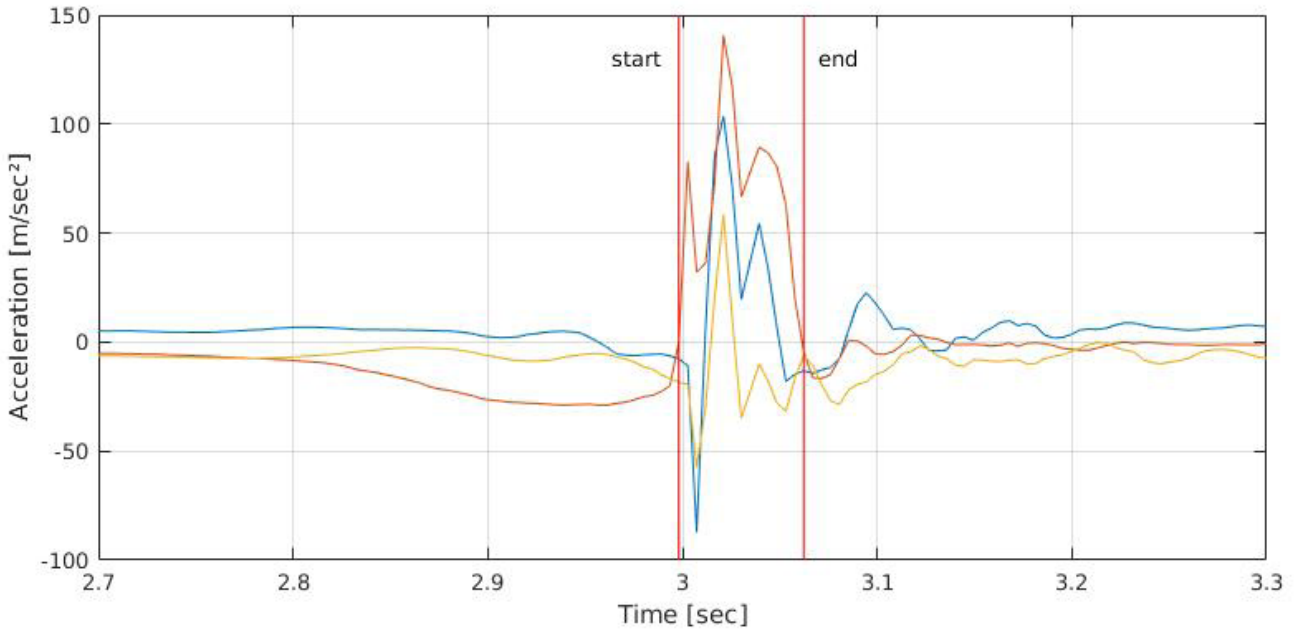


Figure 17 Timeseries of the linear acceleration with impact event of BP 101_1. Start and end of the impact phase are indicated by the red vertical lines.

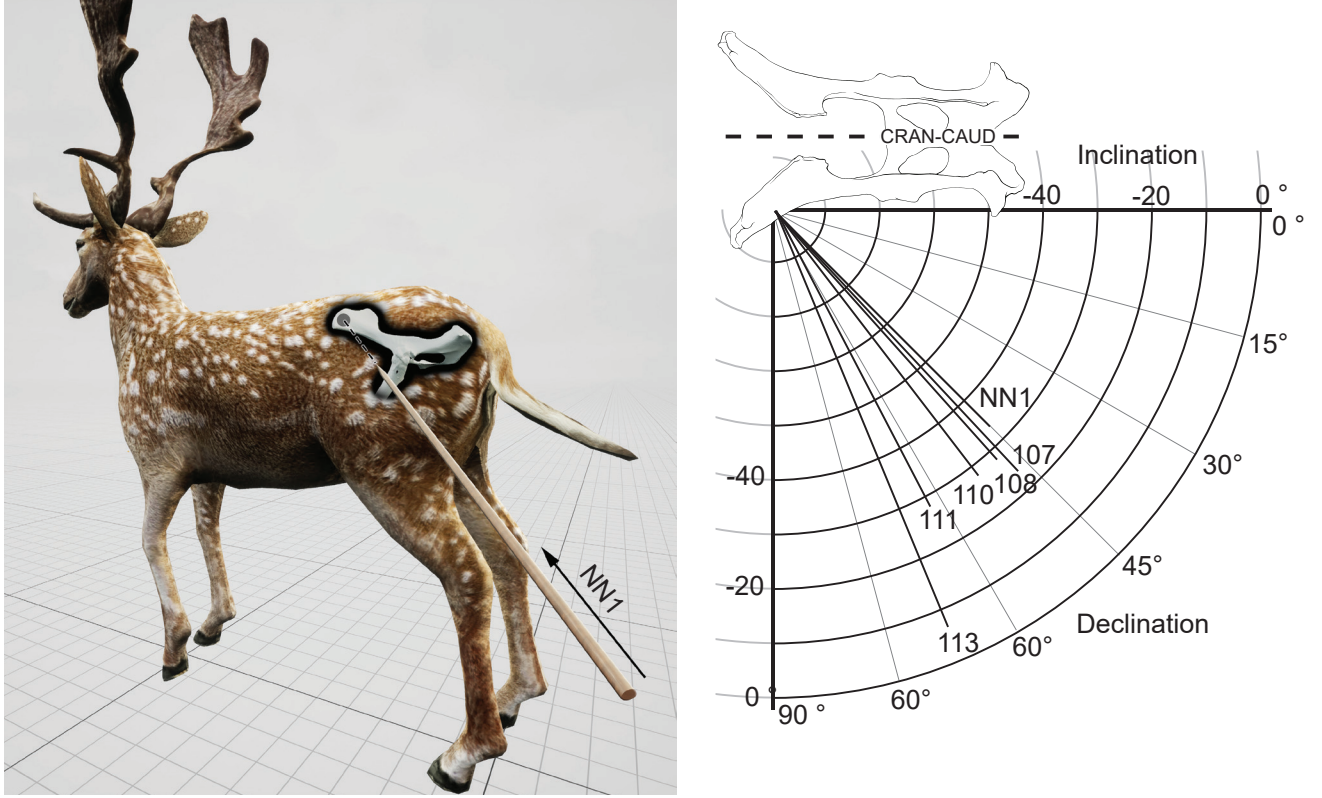


Figure 18 Measured impact angle of the NN1 hunting lesion shown in relation to a standing fallow deer (left), and (right) in comparison with the measured impact angles of the experimental pelvis targets.

$F(t) \in \mathbb{R}^3$ is the force and $v(t) \in \mathbb{R}^3$ is the velocity trajectory of the spear tip. Both trajectories are multiplied using the scalar product inside the integral. t_{start} and t_{end} denote the time phase between the start of the impact event until the spear has come to a complete stop. The difference between calculated (theoretical) kinetic energy and *work on target* is taken as an approximation for additional mass transference by the participant.

Angles of the spear at impact were extracted from the orientation data and transformed to declination and inclination values. Those values describe resp. the angle between spear and the imaginary cranial-caudal line as seen from above (180° - 0°) and the angle between the spear and the surface (0° , range from $+90^\circ$ to -90°) both from an anatomical perspective (cf. **Figure 18**).

3.2.4 Bone target analysis

SAMPLE PREPARATION

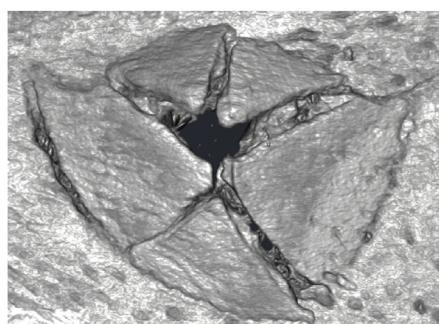
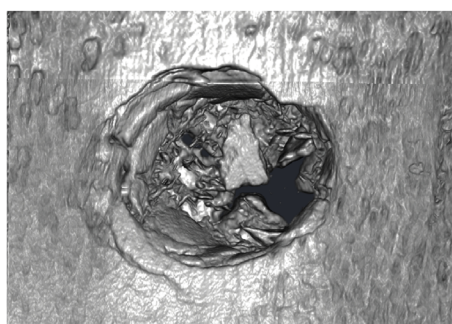
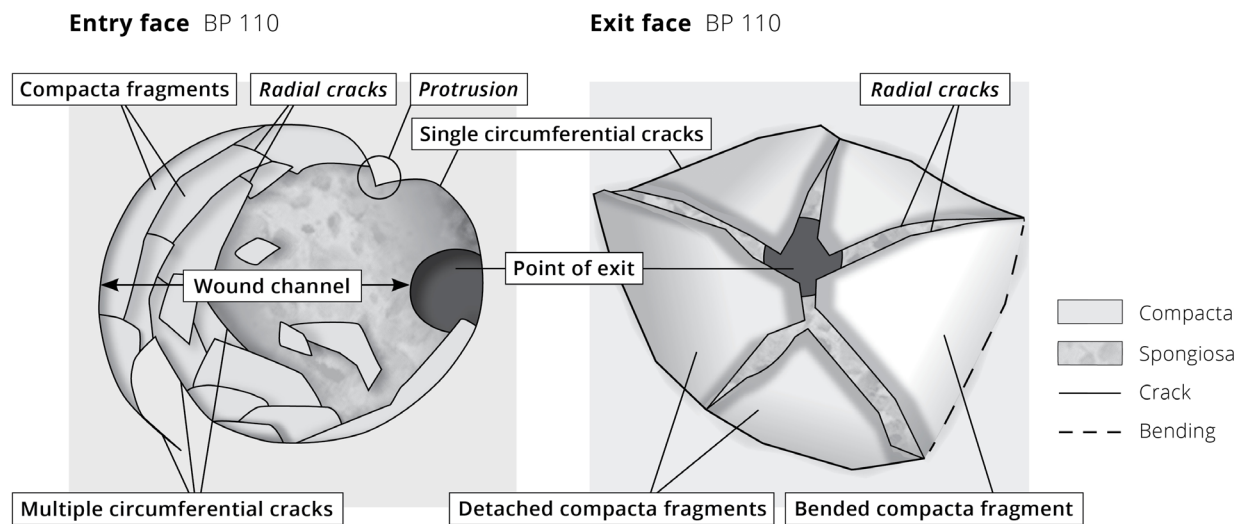
After the experiments, the targets were photographed to document the damage. Subsequently the gelatine was carefully removed. The bone targets were again photographed to document the damage to the hard tissues specifically. Further sample preparation steps were taken for two samples (108 and 110), consisting of the careful simmering of bone samples in soap and hot water (see **Figure 19**) for a duration of 8 hours to mimic organic decomposition and study its effects on the lesions.

DESCRIBING POSITION OF THE WOUND AND IMPACT MARK TYPE

During a first inspection of the material, the *impact mark type* was recorded for all bone targets. *Impact mark types* include: *drags*, *punctures*, *perforation*, *cracks* and *fractures* (see **Table 4**). The position of

Table 4 Quantitative and qualitative variables defined for the description of the experimentally obtained wounds

Impact mark type ⁴⁷	a) <i>drag</i> <i>drag-notch</i> b) <i>puncture</i> <i>puncture-notch</i> c) <i>perforation</i> <i>perforation-notch</i> d) <i>crack</i> e) <i>fracture</i>	Linear mark due to bone surface removal or compression. The addition of the term "notch" indicates the location of the drag on the edge of a bone. Punctiform mark of various depth on bone surface. The addition of the term "notch" indicates the location of the puncture on the edge of a bone. Punctiform lesion due to complete bone penetration. The addition of the term "notch" indicates the location of the perforation on the edge of a bone. Linear mark of various depth on bone. Linear fraction due to complete bone cracking.
Impact mark outline ⁴⁷	a) round b) half-round c) triangular d) rectangular e) square f) polygonal	Impact mark outline on the entry face in bird's-eye perspective
Impact mark size	Max. length per face Max. width per face	Maximum length and width in mm measured with callipers.
Impact mark type cross section		
Cross-section shape	a) \/ b) c) /\ d) ><	Impact mark type cross-section from lateral.
Cross-section symmetrie	a) asymmetrical b) symmetrical	
Fragmentation		
Location of bone fragments per face	a) on entry face b) in wound channel c) on exit face	Bone fragments associated with lesion.
Number of bone fragments per face	a) N_Frag_detached=	Detached bone fragments are counted.
	b) N_Frag_bended=	Bended bone fragments are counted.
Embedding		
Embedded material in lesion	a) yes b) no	Parts of the tip stuck into the lesion which could not be removed. If present specify embedded material type in remarks.
Type of embedded material	a) wood	Identify embedded material.
Radial cracks [RC] ⁴⁸		
Location of RC	a) on entry face b) on exit face c) on entry and exit face	Linear cracks that radiate from the impact point.
Number of RC per face	N_RC_en/ex	Number of <i>radial cracks</i> per face
Number of RC extending beyond CC per face	N_RCex_en/ex:	Number of <i>radial cracks</i> per face extending beyond <i>circumferential cracks</i> . This type is described in the text as extensive <i>radial crack</i> .
Circumferential cracks [CC]		
Location of CC	a) on entry face b) on exit face c) on entry and exit face	Crack-lines circumfering the impact point resulting from transversal breaks between <i>radial cracks</i>
Shape of CC	a) symmetrical b) asymmetrical	Shape of <i>circumferential cracks</i> on entry and/or exit face.
Number of CC per face	N_CC_en/ex	Number of <i>circumferential cracks</i> .
Diameter of CC per face	D_en/ex_min= D_en/ex_max=	Minimum diameter in mm of the outermost <i>circumferential crack</i> .
Number of protrusions per fac	N_Pro_en/ex:	Number of <i>protrusions</i> at the interface of <i>radial</i> and <i>circumferential cracks</i> per face.



Before simmering
(micro CT scan)



After 2h simmering



After 8h simmering

1 cm

Figure 19 Top: Schematic drawing of entry and exit face and nomenclature used. Middle: Micro-CT scans of BP 110; Bottom: Soft tissue removal due to 2 and 8 hours of simmering. Note progressive bone flakes detachment on exit face in the photographs compared to the CT image, where the soft tissue held bone flakes in place.

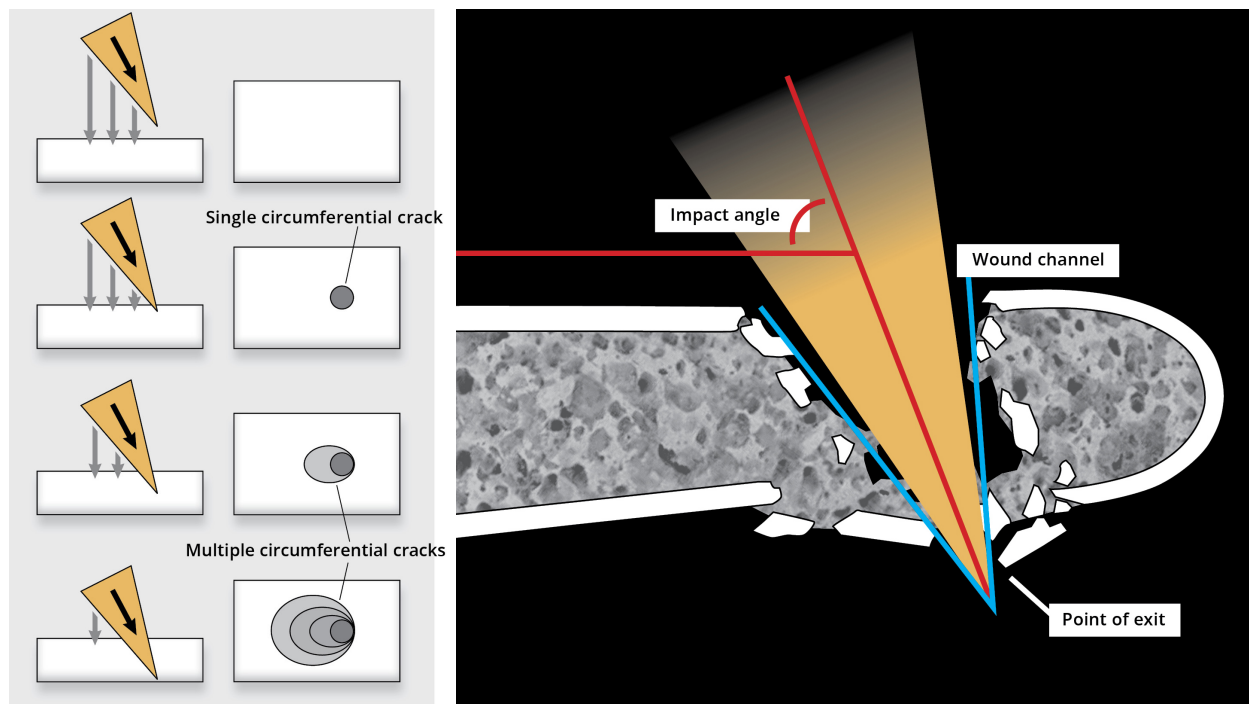


Figure 20 Left: Schematic drawing of the causal relationship between spear-impact angle and *circumferential cracking*. Right: Procedure for the estimation of spear-impact angle.

the *impact mark type* was recorded on a schematic drawing of an *Os illium* and scapula (Figure 21-24) to facilitate the analysis of the relationship between the anatomical position of the impact, the impact mark types, and the spear data (velocity, work on target).

DESCRIBING WOUND MORPHOLOGY

The detailed evaluation of some features found in the wound channel and on the exit face of the lesion, including small fragments, required CT scanning (see Methodology).

For the description of wound morphology, whether by visual inspection or through CT images, a catalogue of traits was used, specifically compiled for this analysis (Table 4). This catalogue includes the revised terminology of earlier studies⁴⁷ and new attributes. Most importantly, a more comprehensive and detailed description of cracks was required (type and abundance of cracks), as they provide a strong indication for the amount of kinetic energy absorbed by the medium⁴⁸. The terminology used for the description of cracks is derived from experimen-

tal studies in the field of fracture mechanics⁴⁹. The accompanying Figures 19 and 20 illustrate these key characteristics and the nomenclature used.

IMPACT ANGLE ESTIMATIONS BASED ON WOUND MORPHOLOGY

The eccentric outline of a lesion (in frontal view; e.g. Figure 19, 20) can result from an acutely-angled impact. Here, the surface of the impacting object is larger on the lower-angled side. Therefore, the transmission of kinetic energy at this position is higher than on the higher-angled side. The eccentricity of the lesion correlates with the inclination and declination of the spear at impact. To estimate these angles in the archaeological material as well as in the experimentally damaged targets, a conical tip with a similar angle of convergence as the tips used in the experiments was fitted to a thinner rod of wood. After positioning and fixing the bone target in anatomical position, the rod was positioned in the wound-channel (Figure 20 - right). Recorded were the declination of the spear at impact, which is the angle between the rod and the cranial-cau-

dal axis (180°-0°), and the inclination, which is the angle made between the rod and the surface (0°, range from +90 to -90°).

3.3 Results

3.3.1 Bone target analysis: Pelvises

In total the 14 pelvis targets (BP 101-114) were struck 31 times, of which 16 strikes hit the bone (Figures 21, 22). The other 15 strikes hit the gelatine parts of the target that surrounded the bone. Of the 16 strikes that hit the bone, three did not produce visible damage, while the other 13 produced various types of bone damage. Strikes were directed towards the cranial end of the *Os ilium*, but half of the hits (n=8) were registered on the caudo-inferior part of the bone. Half of these traces (n=4) result from the lateral slip-off of the spear tip towards the edge of the bone. In all cases this resulted in edge damage (see detailed damage descriptions below). The impacts on the cranial end of the *Os ilium* all resulted in *perforation* (n=6), half of which are associated with *extensive radial cracks*.

PUNCTURE

A *puncture* has been produced on one specimen (BP 109; Figure 21) and is situated on the very cranial part in the centre of *Ala ossis ilii*, the location where most of the *perforations* have been recorded.

As the wooden tip remained in the bone after impact, its wound morphology could only be analysed by Micro-CT (Figure 21 - top right). In frontal view the image shows several *circumferential crack-lines* surrounding the round *puncture*. In cross-section the image clearly reveals a slightly asymmetrical u-shaped wound channel. The right-hand side of the wound channel shows higher material density either due to fragments that have been pressed into the wound channel and/or compression of bone material against the wall of the wound channel. Fragments could not be visualized in detail in the Micro-CT images, most likely because the embedded tip is still compressing the bone material.

PERFORATIONS

Five pelvises were perforated (BP 107; 108; 110; 111; 113, Figure 21). These *perforations* range from 9 to 18 mm in maximal dimension on the entry face and from 9 to 18 mm on the exit face (Table 5). The disparity between length and width on the entry side documents an asymmetrical lesion outline.

Four *perforations* are located at the very cranial part in the centre of *Ala ossis ilii*, whereas the perforation of sample BP 113 is situated near its inferior rim. Three of the *perforations* were produced by 'LGM', 2 by 'KF'. In all cases the vertical thrusting mode was used.

The circular compacta rim that outlines the *perforations* on the entry face shows one or multiple *protrusions* (one: BP 107; 108; 110; 111; two: BP113).

Table 5 Dimensions of the *perforations* and *notches* on the entry and exit face (in mm).

Sample	Impact mark types	Entry face		Exit face	
		Length (mm)	Width (mm)	Length (mm)	Width (mm)
107	<i>Perforation with extensive RC</i>	17.7	15.8	13.1	6.0
108	<i>Perforation</i>	9.1	8.5	8.8	8.5
110	<i>Perforation</i>	10.5	11.9	17.7	11.3
111	<i>Perforation with extensive RC</i>	10.3	13.8	8.8	3.7
113	<i>Perforation with extensive RC</i>	13.6	10.0	11.0	8.5
101	<i>Perforation-notch</i>	15.8	5.0	16.9	9.4
105	<i>Perforation-notch</i>	17.5	9.8	19.6	14.2
112	<i>Perforation-notch</i>	16.2	6.9	19.2	17.5

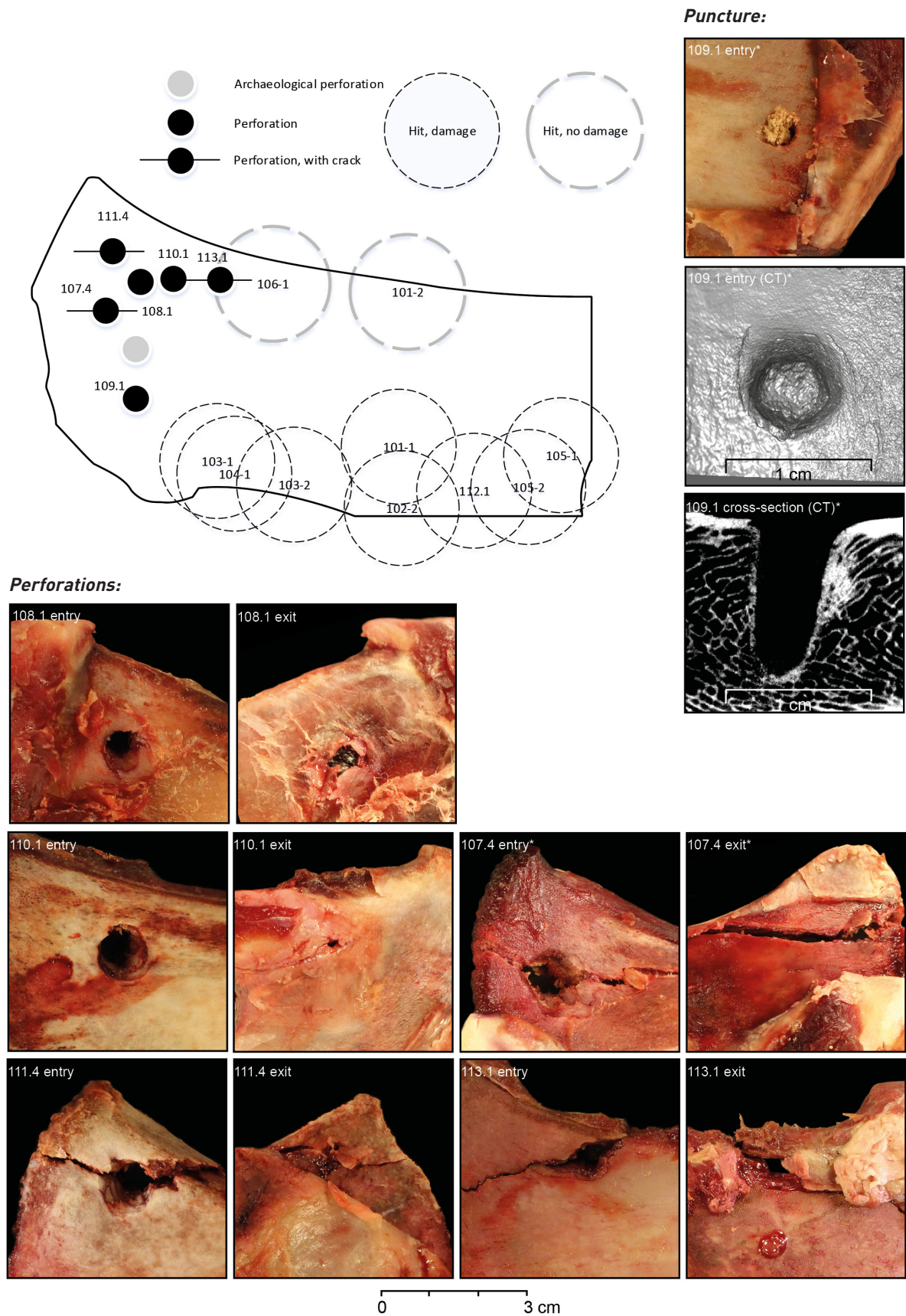


Figure 21 Impact mark types on pelvis targets (1/2): *puncture* and *perforations* and their anatomical location. BP 108 and 110 are shown in detail in Figure 19 after simmering.

Multiple circumferential and radial cracks can be observed in all five *perforations* when viewed from the entry face. This cracking produced multiple bone fragments that were pressed into the wound channel. The wound channels are conical in cross-section. In contrast to the entry face, where *circumferential cracking* appears in all perforated samples, the exit face only has *circumferential cracking* on three samples (BP 110; 111; 113) and results in completely dislodged compacta fragments. On the other two samples (BP 107; 108) *radial cracks* can only be observed on the exit face. Here the compacta showed outward bending but remained attached.

Besides the similarities in the morphological characteristics of the *perforations*, the samples differ in the presence of *radial cracks* extending from the *perforation*. Three of the lesions are accompanied by two *radial cracks* running from the *perforation* outwards and are oriented parallel (BP 107) or oblique (BP 111; 113) to the cranial-caudal, longitudinal axis of the bone. In the case of BP 107, *radial cracking* was extensive but did not lead to fragmentation. This is in contrast to BP 111 und BP 113, which showed the complete detachment of a part of the pelvic bone. Two samples lacked *radial cracks*. A comparison of the size of the *perforations* on the entry faces shows a correlation between the extent of *radial cracks* and penetration depth (Table 5).

CRACKS

The *impact mark type cracks* was observed four times on three bone samples (BP 102; 103; 104, Figure 22). All cracks are located on the dorsal part of the bone where the *Tuber sacrale* has been cut off. They result from grazing contact with the impacting thrusting spear and either form a semi-circular crack-line (BP 104), multiple curved and straight crack-lines (BP 103) or a rectangular crack-line (BP 102) surrounding a still attached compacta flake (Figure 22).

PERFORATION-NOTCHES

Perforation-notches are semi-circular fractures on the edge of bones found on both the entry and exit face. *Perforation-notches* can be found on three tar-

gets (BP 101; 105; 112, Figure 22). The notches measure between 16 and 18 mm on the entry face and 17 to 20 mm on the exit face (Table 5). Similar to *cracks*, notches were only observed on the dorsal area of the *Os ilium* of the bone where the *Tuber sacrale* was cut off. The entry face of BP 101 and 112 show similar *protrusions* as found in full *perforations*.

Perforation-notches are accompanied by *circumferential cracks*. On the entry face of target BP 101, which is situated on the lateral face of the *ilium*, a single *circumferential crack* is visible. Targets BP 105 and BP 112 are characterised by two *circumferential cracks*. The mechanisms responsible for *circumferential cracks* continue on the exit face, resulting in bone *bending* and *radial* and *circumferential cracks* with flaked bone compacta.

On the exit face of BP 101 the diameter of the *perforation-notch* is larger than on the entry face (Table 5). The lesion bevelled due to detached bone compacta. The detachment of bone compacta can also be observed for target BP 112 (Figure 22). In the case of BP 105, the bone compacta on the exit face is still attached.

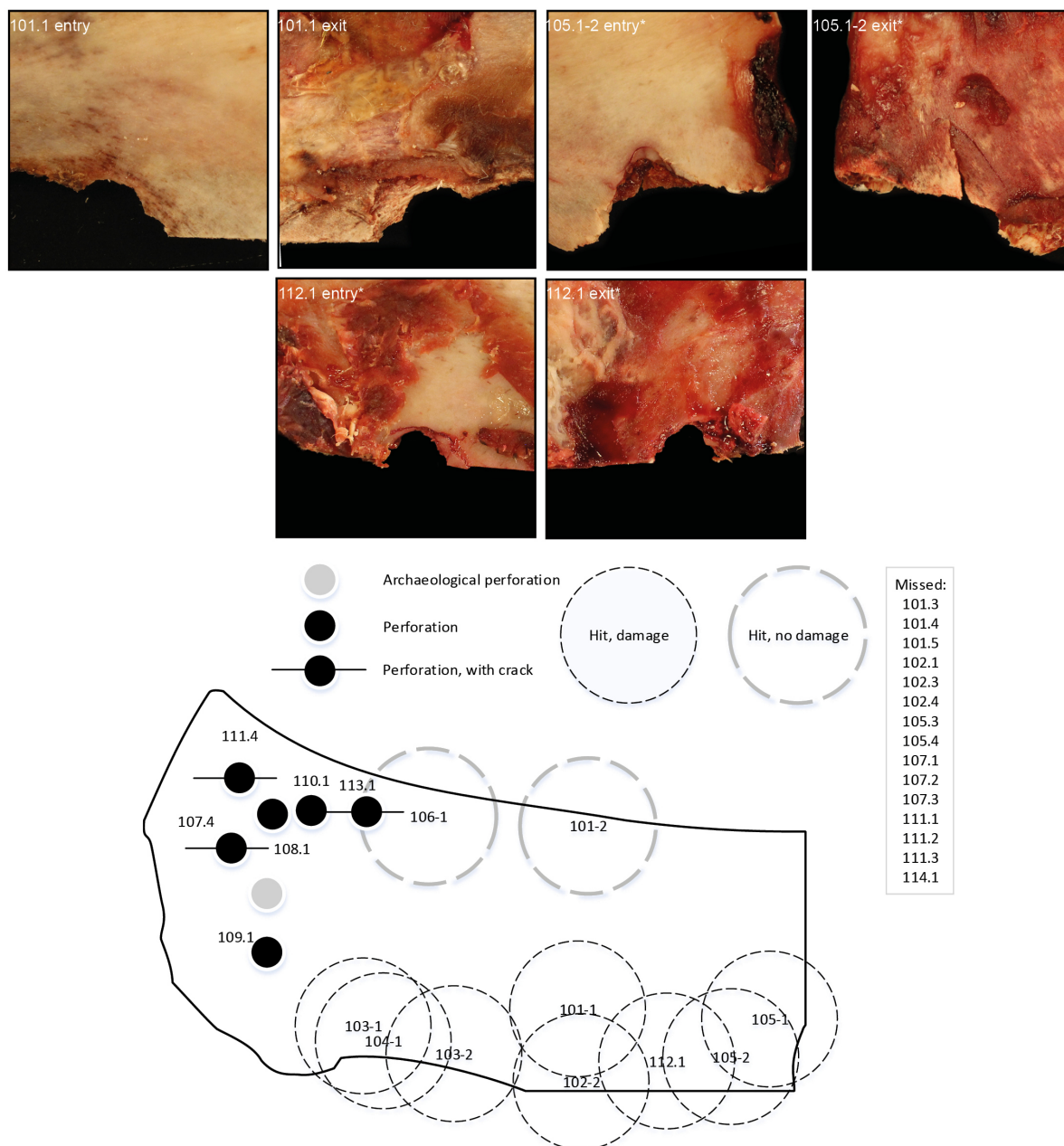
3.3.2 Bone target analysis: Scapulae

In total the 10 scapula bone targets (BS 115-124) were struck 10 times (Figure 23, 24). Five experiments were conducted in horizontal (BS 115-119) and a further five in vertical (BS 120-124) thrusting mode. In eight cases the bones were impacted on the *Fossa infra spinam*. In two cases the spear point only grazed the bones distal part near the edge of the fragment, where it was cut-off. The different impact modes result in two different types of lesions, which are *perforations* (n=8) and *cracks* (n=2). The *perforations* differ in morphology from each other and will be described below in detail.

PERFORATIONS

Eight scapulae (BS 115; 118-124) were perforated (Figure 23, 24). The *perforations* are located in the centre (BS 115; 118; 120; 122), in the distal 1/3 (BS 119; 124) or in the dorsal 1/3 (BS 121; 123) of the

Notches:



Cracks:

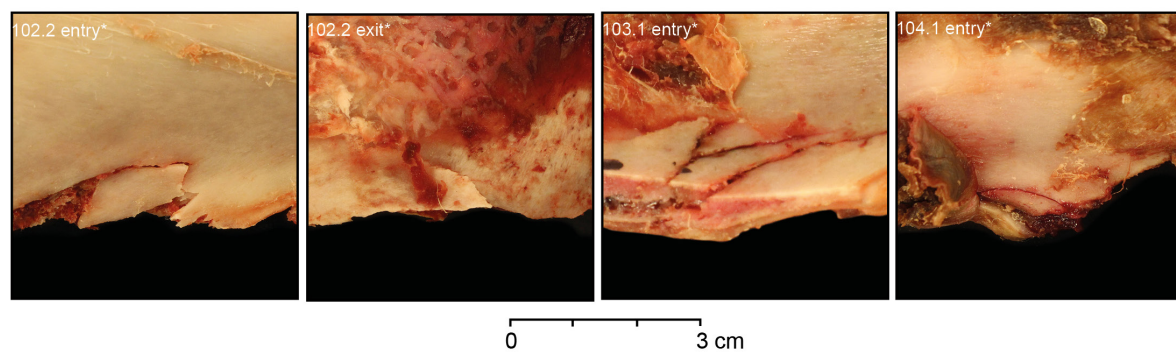
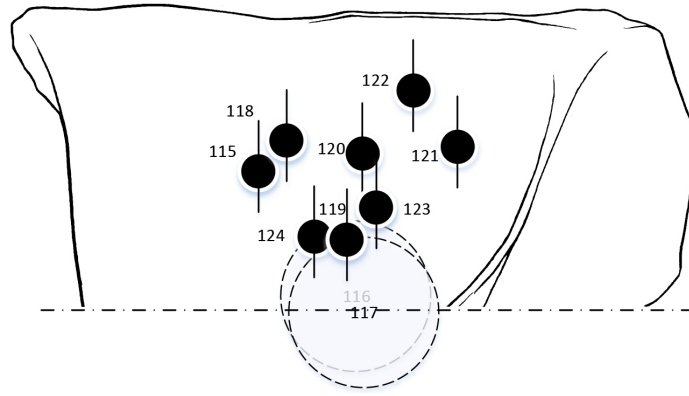


Figure 22 Impact mark types on pelvis targets (2/2): perforation-notches and cracks and their anatomical location



Perforations:

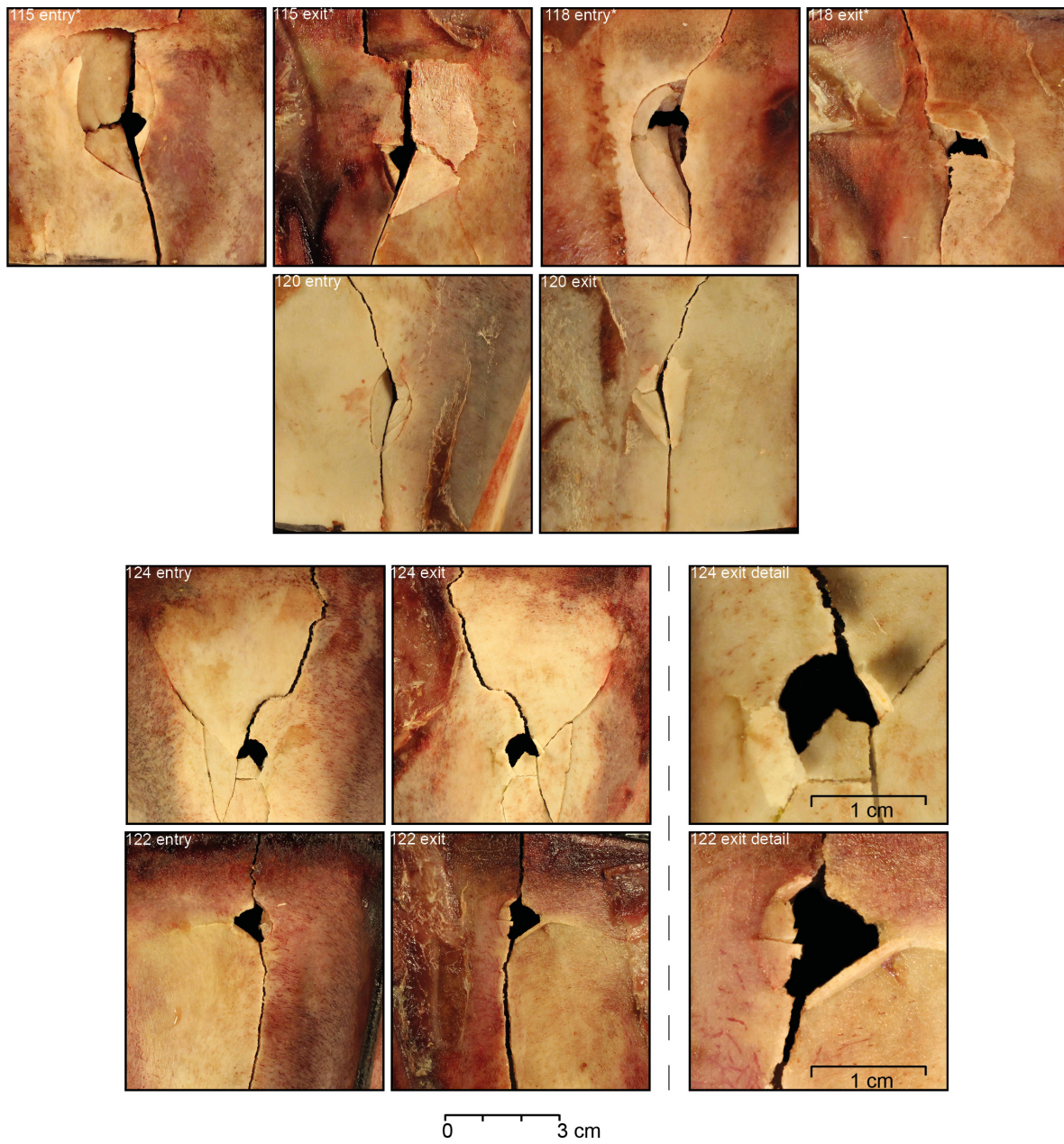
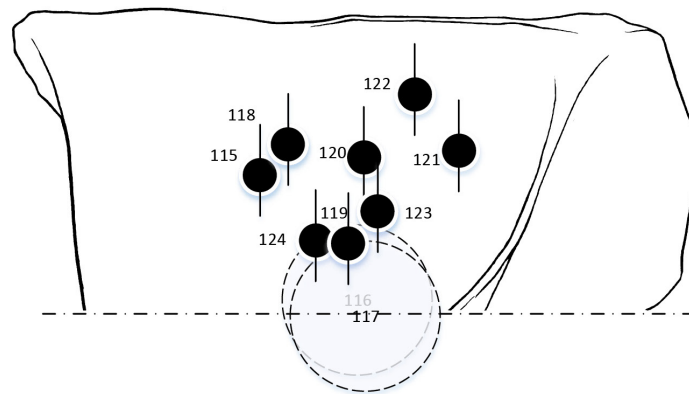
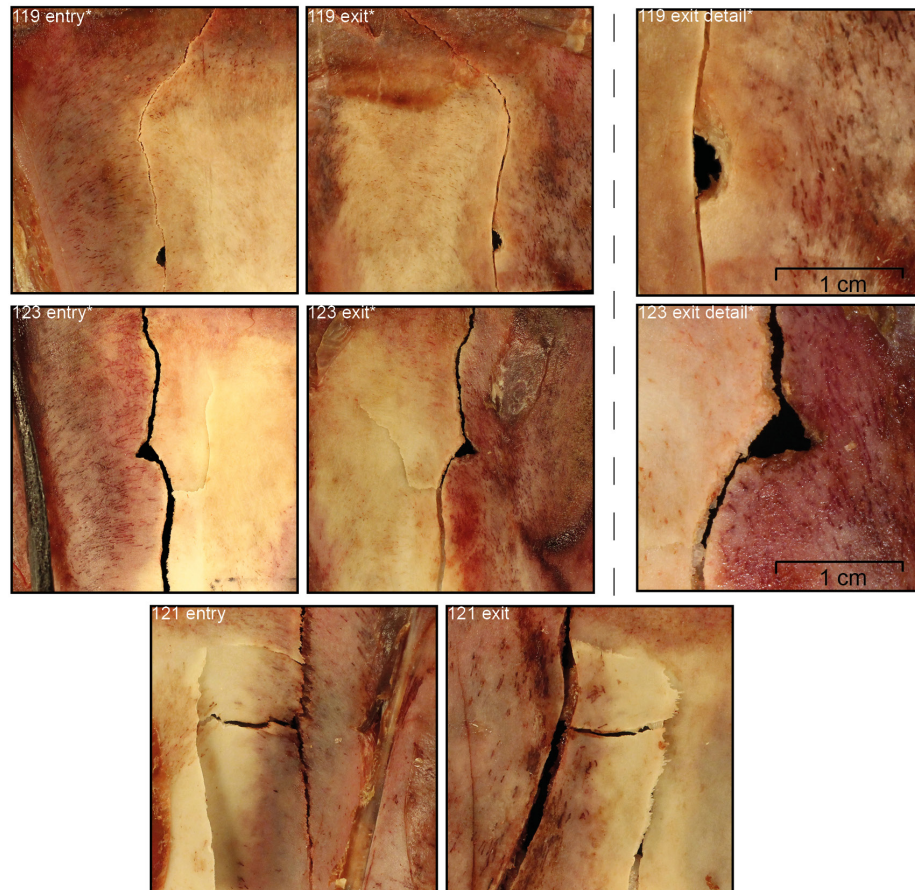


Figure 23 *Impact mark types on scapula targets (1/2): perforations with multiple circumferential and extensive radial cracks and their anatomical location.*

Perforations (cont.):



Cracks:

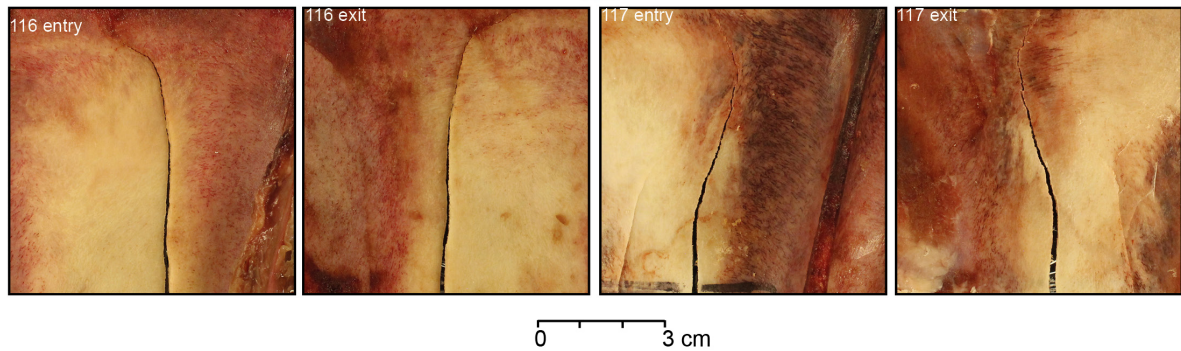


Figure 24 *Impact mark types on scapula targets (2/2): perforations with extensive radial cracks and cracks and their anatomical location*

Fossa infra spinam. The *perforations* vary in size and shape. They are accompanied by the same *impact mark type* characteristics as documented for the *perforations* in the pelvises, i.e. the asymmetrical extent of the *circumferential cracks* around the *perforation* and attached or fully dislodged bone compacta on the exit face, due to bone bending or persisting *circumferential cracking*.

Radial cracks run from the impact point to *circumferential cracks*, but can also extend well beyond it. As illustrated by targets BS 115, 118 and 120, *protrusions* form at the interface of *circumferential* and *radial cracks* (Figure 23).

In the absence of *circumferential cracks*, the *perforation* produced in BS 121 differs from the other samples as only *radial cracks* have been observed (Figure 23).

CRACKS

The *impact mark type* “*cracks*” is found on two scapulae-targets (BS 116; 117; Figure 24) that were damaged by horizontal thrusting which failed to perforate the bones. The spear point contacted the distal rim of the bone samples. For target BS 116, the kinetic energy of the spear sufficed to produce one *radial crack* along the longitudinal bone axis (distal-dorsal) parallel to *Spina scapulae*. For BS 117 the impact dynamics produced two longitudinal *radial cracks*.

3.3.3 Impact angle estimations

The declination of the estimated impact angles for the pelvis bone targets with *perforations* range from ca. 45 to 70 degrees, but most are between 45 to 55 degrees (Figure 25). The estimations therefore suggest that the bone targets were all struck in an oblique angle from a caudo-lateral position, independent of the thrusting mode. The inclination of the spear at impact ranged from ca. 10 to 30 degrees, but most hits registered around 25 degrees. These values indicate that with the animal standing upright, the base of the spear faced downwards and thus the tip upwards.

For the impact angle of the hunting lesion observed on the NN1 pelvis, a declination of 45 degrees and an inclination of 33 degrees could be reconstructed. This impact angle is very similar to the experimentally obtained impact angles in samples BP 107, BP 108 and BP 110 (Figure 25).

The manually estimated impact angle values for the *perforations* are indicated in black in Figure 25, whereas the digitally measured impact angle values for the spear (see section 2.4.3) are indicated in red. The systematic deviation between both datasets can be attributed to the different ways they are obtained: the estimated angles correspond to anatomical position, whereas the impact angles obtained

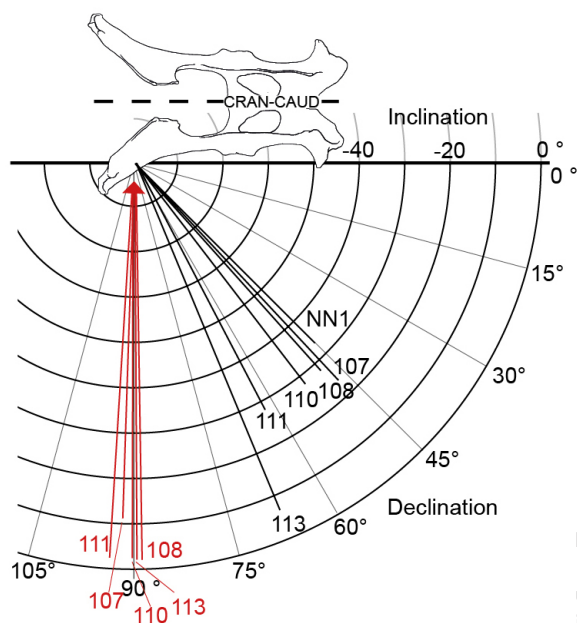


Figure 25 Impact angle of the experimentally-produced *perforations*; a comparison based on the spear data (red) and the measured angles (black). The archaeological perforation is indicated in black as ‘NN1’

from the spear data reflect the angle of the spear at impact with the overall target setup (i.e. ignoring potential movement of the bone at impact).

Due to the thinness of the scapulae, it was not possible to estimate impact angles based on the morphology of the wound channel.

3.3.4 Spear sensor data

VELOCITY AND CALCULATED KINETIC ENERGY

In total 41 thrusts were conducted at pelvis (n=31) and scapula (n=10) targets. In 38 cases the spear trajectory was recorded in sufficient detail to calculate spear velocity at impact. The velocities at impact range between 2.2 and 6.8 m/s, of which the latter represents an extreme outlier that was excluded from further analysis. The majority of the values range between 3.6 (first quartile in boxplot: Q_1) to 4.5 m/s (third quartile in boxplot: Q_3) (Median in boxplot: Q_2 = 4.2; **Figure 26 A-I**).

Differences are visible between participants, between thrusting modes, between target types and between absence/presence of damage (**Figure 26 A-I**) for the measured velocities. However, most differences can be attributed to the participant: the higher-velocity attempts were conducted by 'KF', while attempts by 'LGM' yielded lower velocities. Overall, horizontal thrusting produced higher velocities than in vertical mode, but when studied per participant this turns out to be only true for participant 'LGM' (**Figure 26 F**). As all scapula experiments were done by 'LGM', the registered velocities for this target type are lower than those for the pelvis targets which were conducted by both 'KF' and 'LGM'. The lower velocities for the hits that caused damage may also relate to the participant: 'LGM' produced significantly more damage than 'KF' (20/23 and 4/18 respectively).

Thrust that came into contact with the target (**Figure 26 A-II**: 'contact') were achieved with lower velocities than those that missed (**Figure 26 A-II**: 'no contact'), but this is mainly caused by the high number of misses by 'KF' and their higher velocities. Full impacts on bone show the lowest velocities (**Figure 26 A-II**), whereas bone contacts (evident

from damage observed in gelatine) and slip-offs (deviation between point of impact as observed in gelatine and the location of impact mark on bone) are characterized by medium velocities.

Despite small sample sizes, a relationship between velocity and the degree of damage is apparent. For *punctures* and *perforations* on pelvises, there seems to be an increase in the degree of damage with increasing velocity ranging from *punctures* only, to *perforations* with *extensive radial cracking* that finally leads to fragmentation (**Figure 26 A-III-IV**).

Kinetic energy (Joules: J) of the spear could be calculated using its measured velocities and the mass of the spear (3.13 kg). The obtained kinetic energy ranges from 7.6 to 71.8 J, with the latter representing the extreme outlier identified for velocity. The midrange reaches from 21.6 (Q_1) to 31.0 J (Q_3) (Q_2 = 27.8 J; **Figure 26 B-I**). The kinetic energy values follow the same trends as the velocity values (**Figure 26 B-I-IV**).

WORK ON TARGET AND ITS CORRESPONDENCE TO KINETIC ENERGY

The *work on target* (W ; in Joules) was measured with the spear sensor for 38 of the 41 thrusts. The registered W -values range from 5.7 to 76.3 J, with most between 28.6 (Q_1) to 59.4 J (Q_3) (Q_2 = 39.5; **Figure 26 C-I**).

Participant 'KF' produced higher W -values than 'LGM'. Higher W -values were measured for horizontal thrusting compared to vertical thrusting. Higher W -values were observed for BP-targets in comparison to BS-targets. These patterns observed in the work on target values for individual categories i.e. participant, thrusting mode and target are also reflected in velocity values (**Figure 26 C-I**). The explanation provided for the differences in the velocity data can also be applied as an explanation for differences in work on target values.

Thrusts that contacted the bone target (**Figure 26 C-II**: 'contact') are characterized by lower W -values than thrusts that missed the bone (**Figure 26 C-II**: 'no contact'). Full impacts that resulted in bone *perforation* and *punctures* show lower W -values than full impacts where the spear slipped off the bone

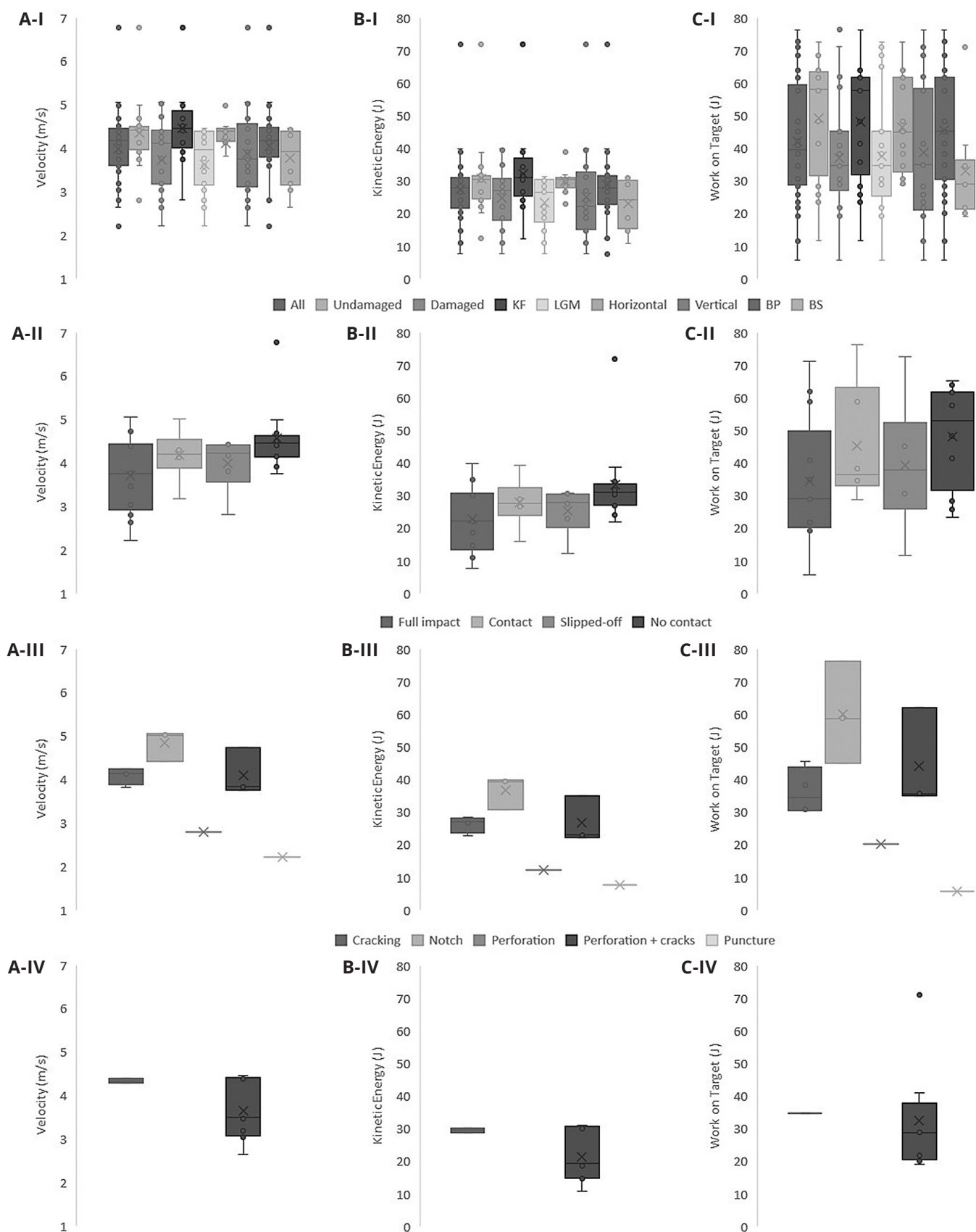
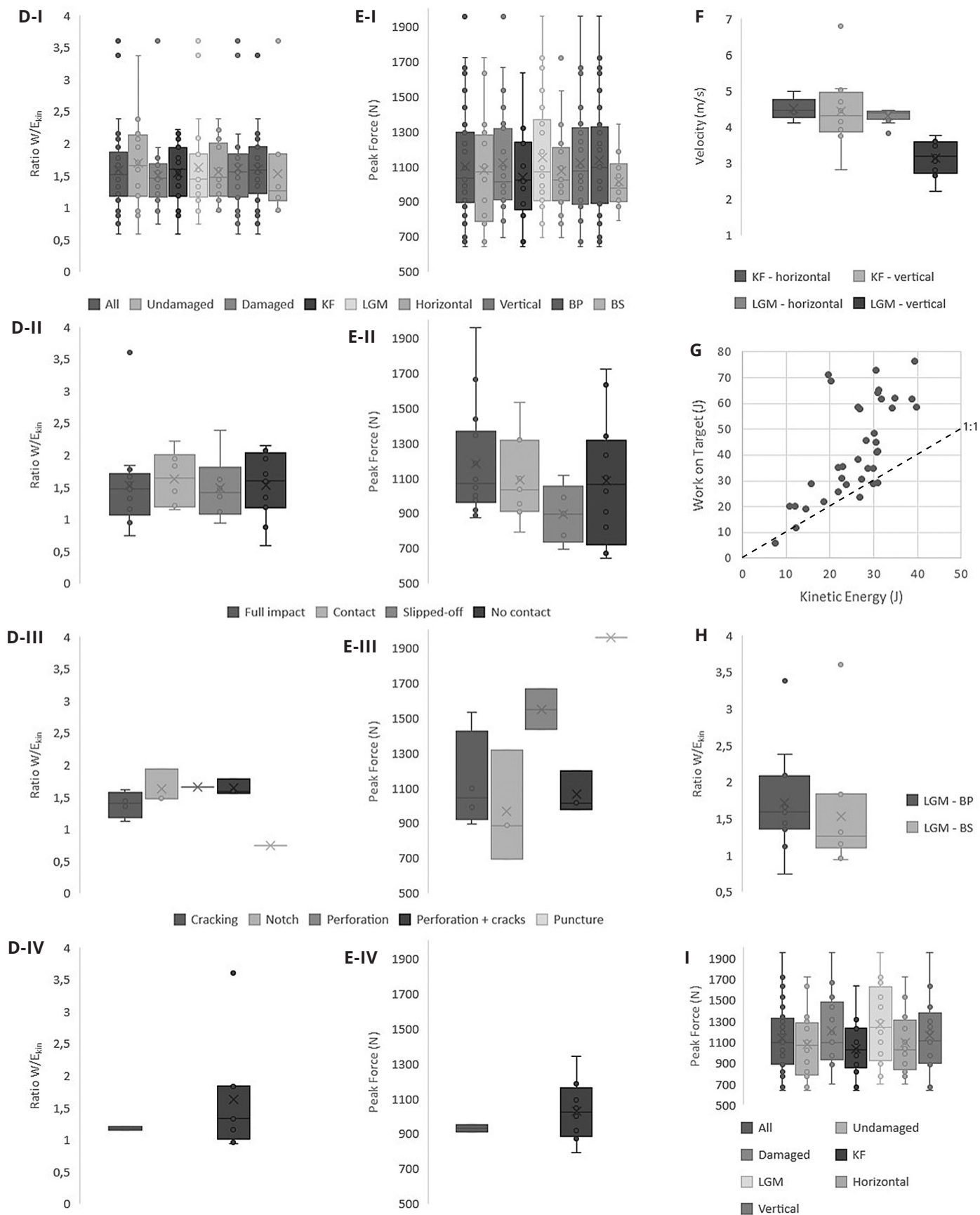


Figure 26 boxplots of the velocity (m/s), Kinetic Energy (J), work on target (J), ratio between the calculated and Kinetic Energy and Work, and Peak Force (N).



(Figure 26 C-II: 'slip-offs') or hits that contacted the target only laterally (Figure 26 C-II: 'contact').

Despite small sample sizes, a relationship between *W*-values and the degree of damage is apparent. For *punctures* and *perforations* on pelvises, there seems to an increase in the degree of damage with increasing *W*-value ranging from *punctures* only, to *perforations* with extensive *radial cracks* that finally leads to fragmentation (Figures 26 C-III-IV).

For the scapulae, comparison between *impact mark types* in relation to *W*-values does not provide further information due to the homogeneity of *impact mark types* produced: 8 out of 10 observed *impact mark types* fall into the category of *perforation with extensive radial cracks* (Figure 26 C-IV: 'perforation+cracks').

A comparison between kinetic energy and *W*-values (Figure 26 G) shows that *W*-values do not only reflect velocity and kinetic energy alone. *W*-values are either equal to or higher than kinetic energy values. Indicating the transference of additional mass to the spear, i.e. through thrusting mode and the mass specific handling techniques applied by the participant. To study this relationship in more detail, the ratio between *W* and kinetic energy was studied. The ratio ranges from 0.58 to 3.60 and the mid-range covers 1.17 to 1.86 ($Q_2=1.51$; Figure 26 D-I). The average ratio is 1.58 indicating an additional 58% transference of body mass into the spear per impact.

For participants, the *W*-values matches the kinetic energy values, indicating an equal amount of mass transference per individual (Figure 26 D-I). Only "LGM" targeted both BS and BP-targets. It was noted that lower mass was involved in thrusts on BS-targets in contrast to BP-targets (Figure 26 H).

PEAK FORCE

The peak force (in Newtons) represents the maximum value of the force trajectory and is therefore dependent on the interaction between the spear and the target material. Peak force was measured for 39 of the 41 hits, with values spreading from 634.6 to 1953.8 N, of which the latter can be considered an outlier (Figure 26 E-I). The midspread ranges from 895.2 (Q_1) to 1292.0 N (Q_3) ($Q_2=1034.23$).

Of the categories shown in Figure 26 E-I, participant, thrusting mode and target, only target shows strong differences in registered peak forces: the BS-targets show lower forces and a smaller variation in values than the BP-targets. Because of these differences, which are the result of material properties, the variables participants, thrusting mode, and target have also been studied for BP-targets only (Figure 26 I). Again, few differences are visible except for participants: 'LGM' produces significantly higher peak forces than 'KF', reflecting his higher success-rate in perforating bone (see Discussion section 3.4.2.).

Comparable peak forces were measured for thrusts that fully impacted and/or contacted BP- and BS-targets (Figure 26 E-II). When the spear slipped-off the bone, lower peak-forces were registered as energy was dissipated over a longer time frame. Thrusts with 'no contact' show comparable peak forces as than the ones with 'contact', indicating that these peak forces were generated during the encounter of the weapon with the underlying wooden board. Although sample sizes are small, a comparison of the peak forces per *impact mark type* (Figures 26 E-III-IV) shows an inverted signal for *perforations/punctures* when compared to other measured values i.e. velocity, kinetic energy and work on target. Here, *punctures* show the highest peak-force values, followed by *perforations* and *perforations with extensive radial cracks*. *Perforation-notches* and *cracks* have similar force-values as *perforations with extensive radial cracks*.

IMPACT ANGLE RECONSTRUCTION

Based on the spear data it was possible to reconstruct the impact angle between the target surface and the spear. This impact angle was measured by the declination and inclination of the impacting spear in 24 cases (excluding 'no-contact'; see section 3.3.3). The declination values of the spear range from 82.6 to 104.8° but most values ($n=15$) fall between 85° and 95° (Figure 27). The inclination values are even more consistent as they range between -10.3° and -0.3°, with the majority of the values ($n=14$) recorded between -5° and 0°. Despite

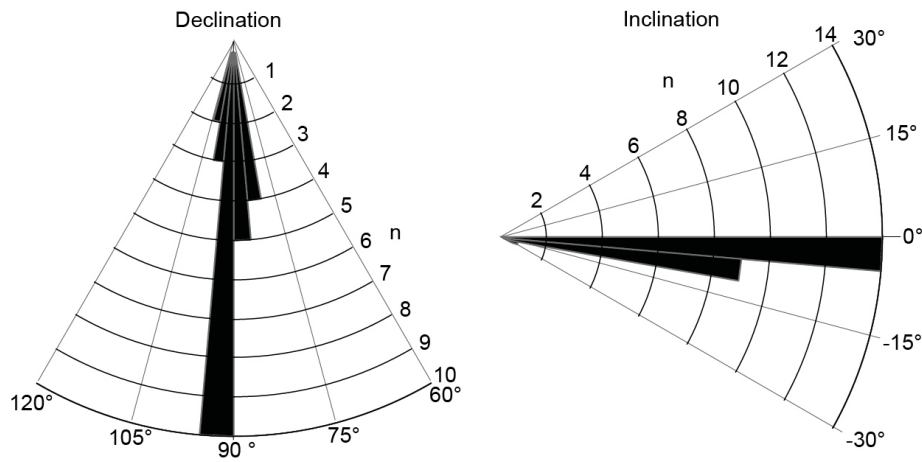


Figure 27 Declination and inclination angles of the experimental spear thrusts

potential differences in thrusting techniques and thrusting modes between participants, the impact angles of the majority of the samples vary in the range of only up to 10°. Therefore, it can be concluded that impact angles are highly consistent.

3.4 Discussion

3.4.1 Velocity and accuracy

Despite the high mass of the spear and the potentially negative effect this has on acceleration, the velocities measured in our study were in accordance with velocities documented in other spear-thrusting experiments (⁴⁴ and references therein). In our experiment, individual participants produced different ranges of velocities and showed different success rates in perforating the pelvis bone target. The higher-velocity strikes of 'KF' missed the pelvis bone targets more often, and caused less damage than the lower-velocity strikes of 'LGM'. One reason for the higher hit- and damage rate for the lower-velocity 'LGM' thrusts could be higher accuracy in hitting the parts of the target prone to damage. For damaging the thin and fragile scapulae, only limited accuracy is needed.

The *perforations* on scapulae were produced in both vertical and horizontal thrusting mode. All *perforations* on pelvis bone targets – which could

only be perforated in a limited area of the bone – were produced by vertical thrusts. This is true even though lower calculated kinetic energies and *work on target* values were calculated for vertical thrusts. As vertical thrusting subordinates spear imbalances due to the unequal mass distribution of the spear (tip with sensors and protective casing versus base) improved accuracy compared to horizontal thrusting may have been achieved. Although the sample sizes for the individual impact mark types are small, an interesting pattern occurred for velocity. The impact mark types associated with the fastest strikes are *perforation-notches* and *cracks*. They were observed on the margin (caudo-inferior part) of the pelvis. For half of the sample it could be demonstrated that the hits have struck the convex part of the bone that is not liable to perforation, thus these hits must have slipped-off to produce the observed *perforation-notches* and *cracks*. This underlines the relationship between the various material properties of the pelvis and their effect on *impact mark types*. The cranial part of the pelvis where the perforation of the archaeological sample was observed, could regularly be damaged by low-velocity hits, as discussed in the following section.

3.4.2 Energetic loading and damage types

Using the velocities and the mass of the spear, it was also possible to calculate (theoretical) kinetic ener-

gies (E_{kin} ; see section 3.2.3). Here, the calculation of kinetic energy is based on a flying projectile, rather than a thrusting spear. They therefore provide the minimum value for the amount of kinetic energy. The thrusting experiments have to take into account the additional transference of mass into the spear by the handler. This study provides for the first-time *work on target* (W) values for ballistic experiments in an archaeological context. These data enable the study of additional transference of mass expressed as the ratio between kinetic energy and *work on target*. On average, *work on target* shows 58% higher energies than expected from velocity and spear mass alone. However, between participants and thrusting modes, differences in mass input were observed, which are most likely the result of the used thrusting technique. Mass input may have also been a (unconscious) decision of the participant based on the assumed properties of the target: participant 'LGM' hit both pelvis and scapula targets, but imbued (apart from velocity) more mass into the strikes that targeted the thicker pelvis bone, than with those that were targeted at the thin scapulae. Such behaviour may be similar to the tendency of humans and non-human primates to modulate the velocity, mass input and hammerstone mass when trying to achieve particular kinetic energies necessary to knap flint or crack nuts^{50,51}.

As addressed before, sample sizes for individual *impact mark types* are relatively small, but patterns are apparent when considering kinetic energy and *work on target*, in particular for *perforations* and *punctures*. The type of damage appears to correspond to the amount of energy working on the target (E_{kin} , W in Joules) (cf.⁴⁴), from *puncture* to *perforation*, to finally *perforation with extensive radial cracks*.

Opposed to velocity and kinetic energy, peak forces are dependent on the (dynamic) properties of the spear and those of the target material. For hard contact-materials the energy transfer from the spear into the target happens fast which causes a

high peak in the force curve (cf.⁵²). For soft materials this process is slow causing a lower peak. This means that hits with similar kinetic energy will produce very high peak values on thick bones, whereas thinner bones will bend and break. These patterns are reflected in the results of the experiments: the thinner bone of the scapula targets all show *cracks* and lower peak forces than those of the pelvises. This explains why the measured peak forces are much higher than those observed by Milks *et al.*⁴⁴ – who used Perma-Gel™^{'''} only – and shows the effect of target material on recorded physical parameters. For the pelvis targets the peak forces show a larger spread, but those associated with impact marks on bones can be ranked according to the degree of deformation. This is especially true for *perforations* and *punctures*. A *puncture* stops the spear instantly, and thus registers the highest peak forces. With *perforations*, *cracks*, and lastly *perforation-notches*, the deformation phase is extended over a longer time span, resulting in a flattened force peak. This extended time span is partly caused by the fact that the spear also penetrates the target material behind the bone.

3.4.3 Perforation formation and characteristics

PERFORATIONS ON PELVISES

The experiments show that diagnostic *perforations* can only be produced with a wooden thrusting spear when the pelvis is hit in the right spot – in this case the cranial end of the *Os ilium* where the bone is thin and the bone-surface concave. Despite higher velocities, kinetic energies, and *work on target* values, hits on thick, convex bone compacta resulted in the absence of immediate damage. This illustrates the importance of the material characteristics in the formation of lesions, and perforations in particular, and provides an explanation for the scarcity of lesions in the archaeological record.

The diameter of the *perforations* on the entry face is directly related to the penetration depth of the tip, which could be confirmed by photo- and video

^{'''} simulant used in ballistic testing and approximates the performance of 10% (by mass) gelatin⁴⁰

documentation during and after impact. Everything else being equal, penetration depth and wound size are the consequence of energetic loading. Although based on a low number of data points, a moderate correlation between *perforation* size and kinetic energy can indeed be seen in the experimental results (Figure 28). Furthermore, the presence of *extensive radial cracks* is strictly associated with higher-energy impacts.

PERFORATIONS ON SCAPULAE

For the scapulae, every strike produced a *perforation* with associated *extensive radial cracks*. These *perforations* share principle characteristics with those produced in pelvises, which are all the result of the universal elastic-plastic fracture mechanism⁵⁵. They illustrate how material characteristics affect lesion formation and morphology. Noteworthy are *protrusions* that mark the intersection between *radial* and *circumferential cracks* (e.g. Figure 23: BS 115). However, in contrast to the pelvises, where the circular outline of the *perforation* on the entry face reflects the shape and size of the impacting wooden tip, in scapulae the

actual *perforation* is in most cases accompanied by elastic-plastic stress field indicated by *extensive circumferential cracks*, that is much larger area than the diameter of the impacting tip. Despite the small sample size, the morphology of this area depends on the kinetic loading of the strike (Figure 29).

3.4.4 Interpretation of hunting lesions: NN1 and the archaeological record

THE NN1 PERFORATIONS

The *perforation* identified on the male adult *Dama dama geiselana* individual (No. 97:14159) shows very strong similarities in size and morphological characteristics with the *perforations* produced in the experimental analysis (see in particular Figure 2 of the main text). On the entry face of the NN1 specimen and the experimentally obtained *perforations*, diagnostic features include unilateral *multiple circumferential cracks*, with bone compacta pressed into the wound channel, opposite *protrusions* marking the intersection between *radial* and *circumferential cracks*. On the exit face of the dorsal-facing part

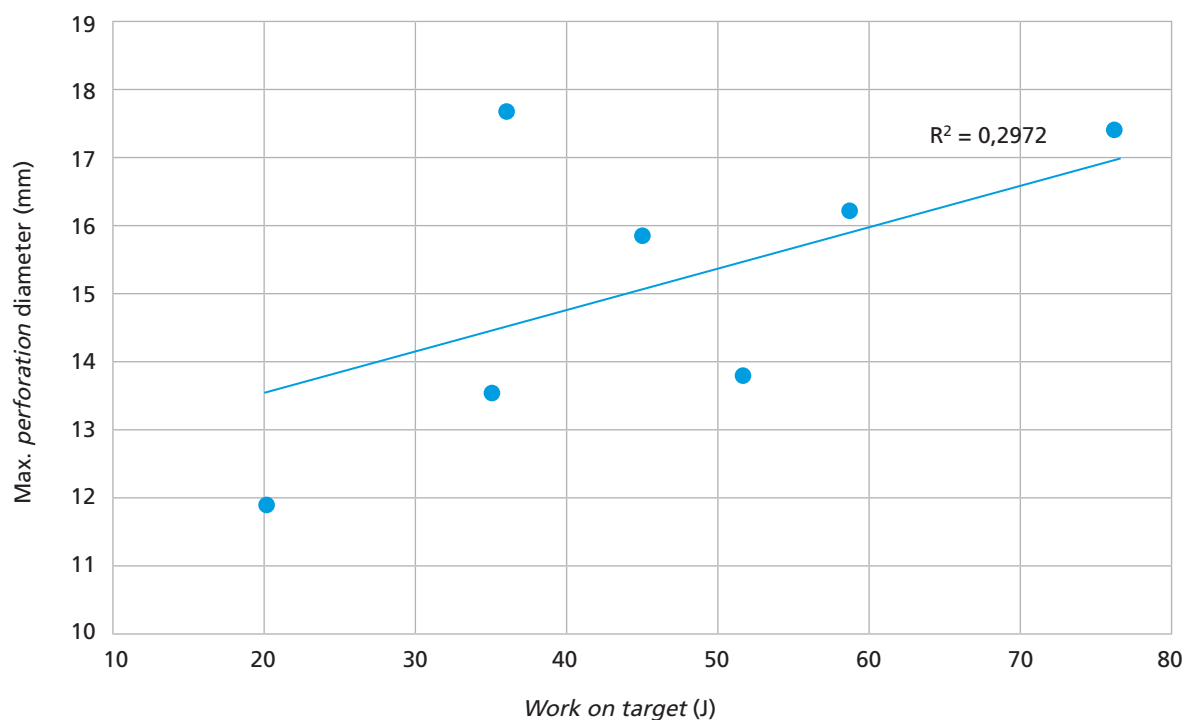


Figure 28 Scattergram of the relationship between *work on target* and the maximum *perforation* diameter of the entry face of the pelvises.

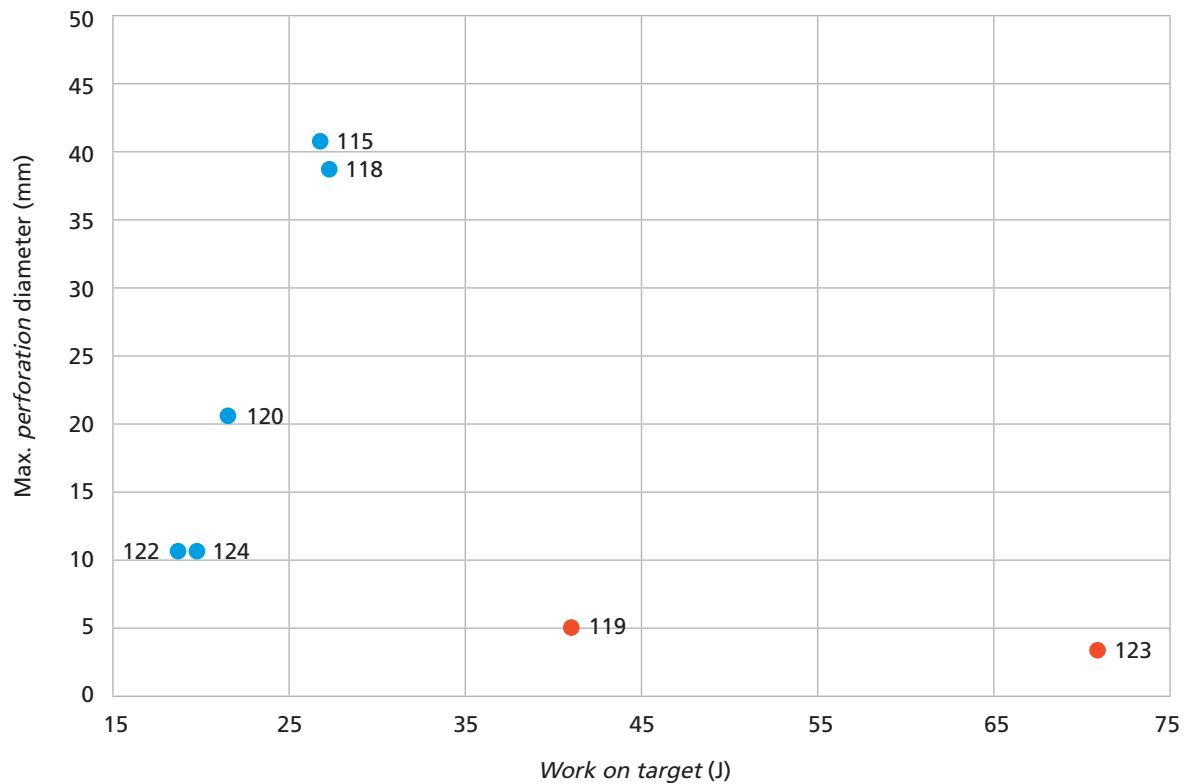


Figure 29 Scattergram of the relationship between *work on target* and the maximum *perforation* diameter of the entry face of the scapulae. *Perforation* BS 119 and BS 123 were produced with substantially higher energies, which resulted in *radial cracking* without *circumferential cracking*, and therefore a smaller *perforation* diameter.

of the *perforation* of the NN1 specimen, bended out though still attached bone compacta can be observed. Caudally, the *perforation* shows a bevelled rim resulting from bone flake removal. Unlike the fracture plane itself, its outline shows an absence of discoloration and/or sediment remains, indicating that this flake became detached only recently.

The diagnostic features of *impact marks* described in this study can also be found in other experimental studies, i.e. high and low velocity projectile and blunt force experiments on osseous^{56,57} and non-osseous target materials (e.g. synthetic bone⁵⁸, glass⁵⁹ and even concrete⁴⁹). The fracture morphologies observed in our experiments must be considered to reflect a universal fracture mechanism. The different cracking patterns described above are identified as the result of transmitted kinetic energy (*W*) spreading in transversal and longitudinal waves – a principle described by e.g.^{60,61}. Based on the similarities between the NN1 lesion and the experimentally obtained *perforations*, we

can consider the latter as being produced by similar dynamic conditions.

The experimental results also demonstrate that diagnostic *perforations*, like the ones found on the NN1 specimens, only form under very particular dynamic conditions. The absence of *extensive radial cracks* beyond the *perforation* in the NN1 pelvis indicates a low-energy impact mark (cf.⁴⁸), which excludes a throwing spear as a potential weapon. This conclusion is further supported by the estimated impact angle of the non-lethal thrust, which is impossible to achieve when the animal is standing (see **Figure 18**), and highly unlikely with the animal in lying position, as the spear has to be thrown with very high precision 16 meter into the air at an inclination of 50 degrees and over a distance of 40 m. The low-energy *impact-mark* in the NN1 specimen is therefore most likely produced by a spear used in a low-velocity, thrusting motion.

A second *perforation* is found on the thin *Lamina ventralis* of the 6th cervical vertebra of a male, adult

individual (No. 88:10). It is similar in size to the *perforation* found on the pelvis and also shows a diagnostic *protrusion*. The morphology of the lesion is always the result of both the impacting amount of energy and the amount of kinetic energy that can be absorbed into the target material. Lesions produced on thin bones are expected to reflect only a minimum of the actual kinetic energy of the impacting object, as most of the energies remain with the projectile after perforating the thin target material. This principle is well-known in wound ballistics³⁸. The effect of bone thickness on lesion morphology has also been demonstrated empirically in forensic studies⁵⁴, showing that the modes of fracture and deformation depend on the properties of the impacting object relative to those of the target (e.g.⁵⁵). It is interesting to note that the outline of the *perforation* in the NN1 6th cervical vertebra differs in form from the experimentally-obtained scapula wounds. This most likely results from differences in bone structure. However, the *protrusion* in the caudo-ventral area of the *perforation* indicates that the object impacted with lower energy, as the very thin bone material absorbed enough energy to develop *radial* and *circumferential cracks*, as indicated by the presence of the *protrusion*. What can be noted however, is the absence of *extensive radial cracks* again underlining low-energy dynamics that correspond to the physical profile of an impacting thrusting spear

SCARCITY OF HUNTING LESIONS IN THE ARCHAEOLOGICAL RECORD

As demonstrated in our experiments, it is possible to perforate animal bones with a wooden thrusting spear. Despite the particular effort to produce a *perforation* as seen in NN1 by trained martial arts and prehistoric weaponry experts, the relatively low number of *perforations* are one explanation for their scarcity in the archaeological record. Moreover, the varying material properties within and between skeletal elements determines the formation of *impact mark types*. As only few bones of the skeleton of a prey species are susceptible to perforation, the chance of finding a diagnostic lesion in the archaeological record is small.

The scapula targets in our experiments showed that they are easily perforated, but are in the thin parts of the blade always accompanied by extensive breakage. This breakage leads to loss of fragments, especially when bones are fully split by the impact. The remaining parts may be diagnostic, but are extremely vulnerable to post-depositional processes, leading to further fragmentation that results in equifinality in the interpretation of the damage. Based on the results of the experiments presented here, it would be possible to evaluate the potential lesion of Boxgrove⁶³, but the fragmentary condition of the scapula carrying this lesion is such that it will never be possible to unequivocally identify it as a hunting lesion. High resolution data from archaeological contexts as observed at NN1 are needed to disentangle such interrelationships.

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