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RESEARCH

Exploring Gravettian Mammoth Rib Tool Production in the Ach Valley (SW Germany) Through Experimental Archaeology

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Abstract
Artefacts made from mammoth ribs are common in Gravettian contexts in the Swabian Jura of southern Germany. The death of the Indian elephant cow *Molly* at the Wilhelma Zoo in Stuttgart presented a rare opportunity to conduct experimental archaeological studies aimed at reconstructing the manufacturing processes of such tools. These experiments were carried out during the workshop *"Processing of Proboscidean Ribs as Raw Material for Tools,"* held at the Museum für Urgeschichte und Eiszeitkunst (URMU). The primary objective was to process elephant ribs in order to gain insights into the *chaîne opératoire* involved in the production of smoothers and points, and to compare the experimental results with archaeological evidence derived from faunal remains and mammoth rib artefacts recovered from Hohle Fels and Geißenklösterle caves. The analysis of the workshop identified three principal stages in the production sequence: (1) the manufacture of a rib blank, (2) the longitudinal splitting of the blank, and (3) the shaping of smoothers or points. While certain technological traits and manufacturing traces produced during the experimental workshop could be identified in the archaeological assemblage, others were not evident. This reciprocal process of experimentation and archaeological analysis proved to be a crucial step in the investigation of the discarded rib material from Hohle Fels and Geißenklösterle.

Keywords Upper Palaeolithic · Organic tools · Swabian Jura · Hohle Fels Cave · *Chaîne opératoire* · Indian elephant Molly

Dedicated to Petra Krönneck († 2018)Petra was an archaeozoologist, close friend and colleague of ours, and initiated the 'Molly-Project.' Unfortunately, she passed away before the project was finished.

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Introduction

Since the early 2000s, organic artefacts from the Gravettian cave sites of the Ach Valley (Swabian Jura) have been a subject of research. A particular area of focus for this work is attempting to reconstruct and understand the *chaîne opératoire* of tools made from mammoth ribs (Barth, 2007; Münzel, 2001, 2004, 2005, 2019; Münzel et al., 2017; Wolf et al., 2016).

After the death of a circa 45-year-old Indian elephant cow in the Wilhelma zoo in Stuttgart (Baden-Würrtemberg, SW-Germany), we had the opportunity to receive a complete elephant carcass for the zooarchaeological comparative collection of the Institute for Archaeological Sciences at the University of Tübingen. Molly was euthanized on July 13th, 2011 after an illness, and was contractually transferred to the university by Wilhelma for scientific research the following day. This situation provided an opportunity to conduct archaeological experiments, for example exploring and reconstructing the production of tools from proboscidean ribs. After transporting the carcass to Tübingen, we selectively froze certain parts of the body (e.g., a complete lower hind foot), in order to preserve the remains for future experiments.

In 2014, we initiated a workshop for students from the University of Tübingen with the topic *"Molly: Processing of Proboscidean ribs as raw material for tools*," which took place at the Museum für Urgeschichte und Eiszeitkunst in Blaubeuren (URMU). Another workshop was conducted in 2017 using the articulated lower hind leg and fully fleshed foot of Molly that we had frozen, in order to reconstruct the efficacy of small, simple stone flakes, similar to those found at Lower Palaeolithic sites in the Mediterranean Basin (Starkovich et al., 2021). The workshop aimed to delivered an exploratory insight into the production of bone tools from the Gravettian, especially of smoothers and points, produced from mammoth ribs.

Archaeological Background

Six caves in the Ach and Lone valleys (Swabian Jura) are known for their UNESCO World Heritage status since 2017: Hohle Fels, Geißenklösterle and Sirgenstein in the Ach Valley and Vogelherd, Bockstein and Hohlenstein- Stadel in the Lone Valley (Conard & Kind, 2017). Major discoveries from the sites include the oldest figurative art (Conard, 2003, 2009; Hahn, 1986, 1988; Riek, 1934; Schmid, 1989), the oldest musical instruments (Conard et al., 2004, 2009; Hahn & Münzel, 1995; Münzel et al., 2016) and hundreds of personal ornaments (Hahn, 1988; Kölbl & Conard, 2003; Scheer, 1986; Wolf, 2015), which represent the richness and uniqueness of the Aurignacian period in the Swabian Jura. The research history of these caves dates back to the end of the nineteenth century and started with excavations by Oscar Fraas in 1861 in Bärenhöhle, located in the Lone Valley (Fraas, 1866).

However, the Ach Valley is also one of the key regions in west-central Europe to reconstruct human behaviour in the Gravettian (Fig. 1). Hohle Fels, Geißenklösterle, Brillenhöhe and Sirgenstein all yielded Gravettian deposits, and provide unique and well-dated insights into the life of hunter and gatherers between 34,000 to 29,000 cal. BP (Conard & Bolus, 2003, 2008; Higham et al., 2012; Richter et al., 2000; Schmidt, 1912). Refits of radiolarite lithic artefacts between sites demonstrate that Hohle Fels, Geißenklösterle and Brillenhöhle were used simultaneously by the same Palaeolithic group, or that groups exchanged their tools within the Ach Valley micro-region (Moreau, 2009; Scheer, 1986). Sirgenstein is also part of this micro-region, which was indirectly demonstrated by Scheer (1986) and Moreau (2009), who found artefacts at the site that belong to the same nodules and reduction sequences as pieces from Brillenhöhle and Geißenklösterle (Fig. 1).

From the Ach Valley sites, scholars have published ample data on the faunal remains (Bertacchi et al., 2021; Boessneck & Driesch, 1973; Münzel, 2004, 2019; Münzel & Conard, 2004a), lithics (Moreau, 2009; Otte, 1981; Scheer, 1986; Schürch & Conard, 2026; Taller & Conard, 2016) and organic artefacts (Barth, 2007; Hiller, 2003; Scheer, 1985; Toniato et al., 2018; Wolf et al., 2016).

Beyond the refitted lithics from Hohle Fels, Geißenklösterle, and Brillenhöhle that point to a connected region during the Gravettian, the osseous technology indicates a homogenous group of people with a common bone industry. One example of this homogeneity is the use of mammoth and mammoth-/rhino-sized ribs as points and smoothers (Barth, 2007; Knecht, 1991, p. 235–237), which are the most important organic tool groups in the Ach Valley (Münzel, 2005). Other organic tools include awls and punches made of reindeer metapodials, punches from megafaunal ribs, adzes and handles made from reindeer antler and perforated batons, so-called 'Lochstäbe' from reindeer antler (Barth, 2007; Barth et al., 2009).

In the Upper Palaeolithic the skeletal element representation of mammoth is considerably biased towards ivory and ribs (Münzel, 2005; Münzel et al., 2017; Wolf, 2015; Wolf et al., 2016), which mirrors different preferences in the use of raw materials during the Aurignacian *versus* the Gravettian (Fig. 2).

While ivory was an important raw material during the Aurignacian for all kinds of everyday tools, such as wedges, retouchers, projectile points, as well as for personal ornaments, figurative art, and flutes (Conard, 2003, 2009; Conard & Rots, 2024; Conard et al., 2004; Dutkiewicz,

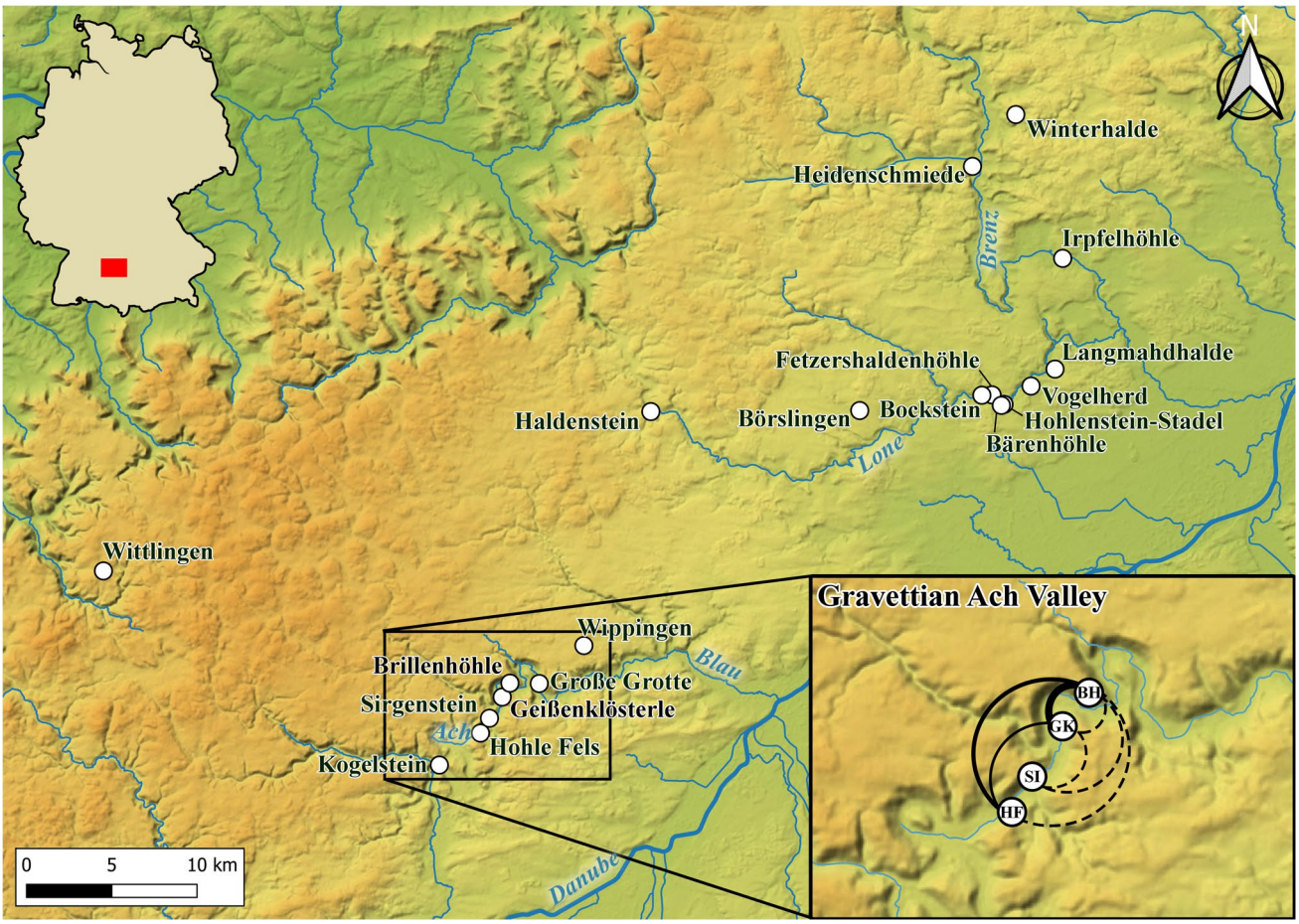


Fig. 1 Paleolithic sites in and near the Ach and Lone Valley (map modified after Schürch & Conard, 2026; background map: https://doi.org/10.5281/zenodo.3460301; copyright ROCEEH/University of Tübingen); Lower right: Lithic refits between Gravettian sites (GK: Geißenklösterle, BH: Brillenhöhle, SI: Sirgenstein, HF: Hohle Fels) in the Ach Valley (solid lines show refits: BH&GK, $n=6$; GK&HF, $n=1$; BH&HF, n=2; dashed lines indicate artefacts that belong to the same nodules, but could not be refitted directly; after Taller et al., 2019)

2021; Dutkiewicz et al., 2018; Wolf & Conard, 2015; Wolf et al., 2025), Gravettian people preferred megafaunal ribs as raw material and rarely used any ivory (Hiller, 2003; Scheer, 1985, 1995). Ivory was mainly chosen in the Gravettian for the production of tear drop-shaped beads (Scheer, 1985, 1995; Vercoutère & Wolf, 2018). These are accompanied by an increasing number of pendants made from animal teeth, which are less frequent in the Aurignacian assemblages (Kölbl & Conard, 2003). Similarly, mammoth rib tools are found in the Aurignacian, but in much lower numbers than in the Gravettian.

The recent discovery from Hohle Fels of an almost complete mammoth rib with 173 markings in two rows and 13 incisions is an outstanding example for the use of ribs in the Gravettian (Conard & Janas, 2018). However, not very much is known concerning the production process of mammoth ribs for tools. Hence, the purpose of this study is to address the use of mammoth ribs in the Gravettian, in particular.

Archaeozoological Background

The pre-LGM (Last Glacial Maximum) Upper Palaeolithic fauna from the caves of the Ach Valley revealed species characteristic for the mammoth-steppe environment, such as woolly mammoth, woolly rhinoceros, wild horse and reindeer, in addition to ibex and chamois, which are well-adapted to the rocky terrain in the Ach Valley. The faunal composition during the Aurignacian and Gravettian periods does not change considerably (Conard et al., 2013; Münzel, 2019; Münzel & Conard, 2004a, b). However, cervid species differ between the two periods, which reflects changing environments. During the Aurignacian, four different cervids, giant deer, red deer, roe deer and reindeer, were present in the Ach Valley. Each of these cervids have different nutritional needs and represents different ecological niches (Immel et al., 2015). During the Gravettian, however, only reindeer and red deer remained (Münzel, 2019). This decrease in species diversity

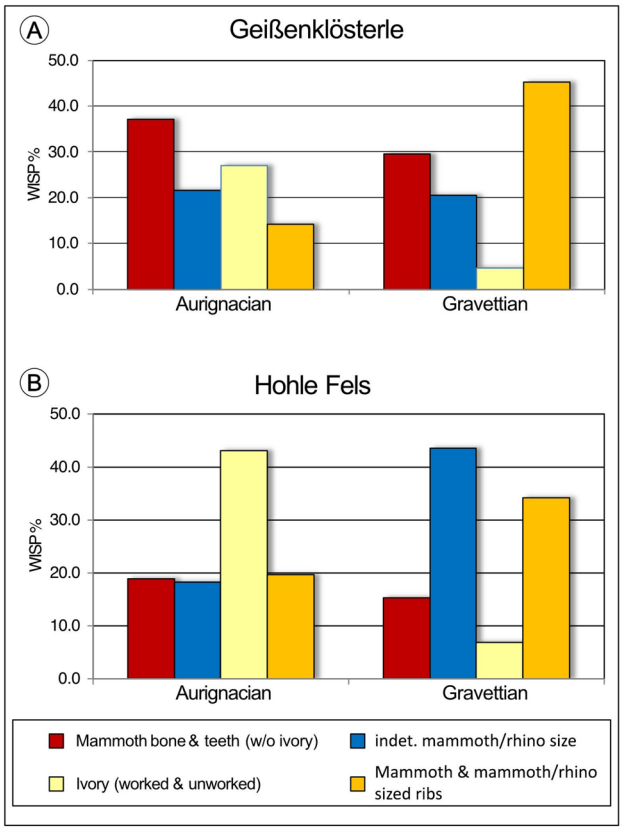


Fig. 2 Comparison of mammoth and mammoth-/rhino-sized remains from Geißenklösterle (**A**) and Hohle Fels (**B**) by anatomical region/raw material type. There is a clear bias towards ivory in the Aurignacian and ribs in the Gravettian. Graphic after Münzel et al., 2017

indicates a climatic deterioration from the Aurignacian to the Gravettian and into the LGM, which is also reflected in the avifauna (Krönneck, 2009, 2019).

After the LGM, the faunal record changed considerably. Large Pleistocene megafauna, such as mammoth and rhino, disappeared, while wild horse and reindeer remained and became the main herbivore species.

The role of mammoth is often underestimated in west-central European sites, simply because its remains are less abundant than at Upper Palaeolithic sites in east-central Europe and Russia (e.g., Leshchinskiy et al., 2021; Svoboda et al., 2005; Wojtal & Wilczyński, 2015; Wojtal et al., 2012). Another reason for the underestimation of mammoth remains is their fragmentary condition and the resulting difficulty to identify those fragments. But preferences of mammoth bone (ribs and ivory) as raw material for artifact production demonstrate the importance of this species in the Upper Danube area.

Mammoth remains are present in all the Ach Valley cave sites, and butchering marks indicate careful processing of this species.

During the course of studying the faunal material of Geißenklösterle (1991–2009) and later Hohle Fels, one of the authors (SCM) noticed distinctive fracture patterns and other features of anthropogenic activity on mammoth rib fragments (Münzel, 2001, 2004, 2005, 2019). This observation, pieced together over years of analysing hundreds of fragments, provided the impetus for an experimental program to better understand the archaeological materials recovered from the Ach Valley sites. This paper aims to identify the *chaîne opératoire* for tools made from mammoth and mammoth-/rhino sized ribs and provide a framework for recognizing the biproducts of such tool manufacture in the archaeological record.

Material

Archaeological Material

The Gravettian megafaunal remains, especially ribs of mammoth and those in mammoth-/rhino-size from Hohle Fels and Geißenklösterle, provide a large amount of production residue (or wasted material), which was part of the manufacturing process for points and smoothers (Barth, 2007; Münzel, 2019).

The archaeological mammoth and mammoth-/rhino-sized remains preserve taphonomic damage that is more consistent with anthropogenic activity as opposed to natural processes (e.g., carnivores, trampling, or rockfall). Following standard taphonomic criteria (Lyman, 1994; Fernández-Jalvo and Andrews, 2016), we would expect trampling damage to consist of shallow, chaotically-distributed scratch marks covering the surface of the materials, in addition to fragmentation that resulted in rib segments that are only rarely split longitudinally. Punctures from carnivore teeth often present an inverted cone-like morphology, and carnivore drag marks on bone surfaces are typically shallow, u-shaped in cross-section, and lack internal microstriations or hertzian cones along the margins (Fernández-Jalvo and Andrews, 2016). Falling rocks can fragment bones, though this should be a rare occurrence in a large assemblage, and would most likely happen when bones are already depleted in collagen, resulting in jagged breaks that occur at right angles to the cortical surface (Lyman, 1994; Fernández-Jalvo and Andrews, 2016).

The mammoth and mammoth-/rhino-size remains from Hohle Fels and Geißenklösterle do not preserve evidence of trampling or breakage through rockfall. Rather, they display features indicative of a primarily

Table 1. Proportion of all identified anthropogenic modifications on mammoth ribs and ribs in mammoth-/rhino-size from Geißenklösterle and Hohle Fels (*anthropogenic modification includes: tools, production debitage, impacts, splitting marks, cut or scraping marks, and knapping marks)

Geißenklösterle (Münzel 2019)	total number	anthropogenic modification *	% modified	carnivore gnawing	weathered, etched, etc.
Gravettian	120	54	45%	5	25
Aurignacian	118	22	18,6%	10	13
Hohle Fels (Münzel, this paper)	total number	anthropogenic modification*	% modified	carnivore gnawing	weathered, etched, etc.
Gravettian	346	203	58,7%	18	43
Aurignacian	78	35	44,9%	5	4

anthropogenic origin. The specimens preserve cuts or scrapes from stone tools, impacts, knapping marks, and marks associated with splitting the bone longitudinally (Tables 1 and 2). Breakage occurred on the materials when the bones were fresh (i.e., green, containing collagen), which is evident through breaks with smooth surfaces and oblique angles relative to the cortical bone (Villa & Mahieu, 1991). Regarding the rare instance of non-anthropogenic damage, one rib was weathered at one end, while the other has a green, tongue-shaped break, which indicates anthropogenic modification in this assemblage (Fig. S4). The only carnivore modifications we recorded were bite marks on the heads of two ribs (Fig. S12 and S14).

This material served as comparison during the workshop for the experimentally produced objects.

Workshop Material

After disarticulation of Molly's carcass and transport to Tübingen, the skeletal elements were buried and covered with 30 cm of sediment to macerate for three years. This caused a brittle consistency of the ribs and left a sticky, whitish, dry fat in the interior spongiosa, which unfortunately had implications for the experiment (see below; Fig. 4E).

For the workshop just left sided ribs of the Indian elephant were used, the right side of the thorax was saved for the University of Tübingen Zooarchaeology reference collection (Fig. 3).

In addition, the participants selected freshly knapped flint flakes that seemed appropriate for their work. Provided to all participants were antler tines with pointed natural ends, wedges (flint, bone or antler), bone chisels, preferably from split deer metatarsals, hammerstones and pebbles, a wooden hammer, as well as sand stone slabs for grinding, and a large boulder in the yard was used as anvil.

Methods

Archaeological Material and its Recording

Two points were especially important for the quantitative analysis of the Geißenklösterle and Hohle Fels faunal remains: 1.) the use of purely descriptive quantitative methods, such as NISP and bone weight, which provides evidence for the biomass for a species or element (Münzel, 1988, 1996; Uerpmann, 1973) and 2.) the inclusion of artificially modified bones that allowed for a better understanding of hunter-gatherer's intentions concerning their choice of game and/or raw materials (see Fig. 2) (Münzel et al., 2017). The quantitative analysis of species and skeletal elements by bone weight demonstrates that anthropogenic selection significantly influenced the faunal assemblage and must be considered before interpreting environmental or climatic evidence of the fauna (Münzel, 2009, 2019).

The identification of the archaeological materials was conducted with the Zooarchaeological reference collection of the University of Tübingen, the Zoologische Schausammlung of the University Tübingen, and the Staatliches Museum für Naturkunde Stuttgart (SMNS). However, mammoth ribs are readily recognized by their thick and 'spongy' compacta. Figure 3d shows a broken bone point (HF56/2597) from the Gravettian of Hohle Fels. In cases when the identification of mammoth was not clear, the size class mammoth-/rhino-size (i.e., megafauna) was chosen.

Experimental Approach – Workshop Design

Aim of the Workshop

The aim of the workshop was to get insights into the production of bone tools from the Gravettian, especially of smoothers and points, made from megafauna ribs, especially mammoth.

Table 2. Hohle Fels ribs with anthropogenic modifications related to tool manufacture and their archaeological provenience. GH = Geological Horizon, AH = Archaeological Horizon. The main Gravettian AH's in Hohle Fels are IIB, IIC, IICF and IID

Figures in the Text	Site and Square	ID	GH	AH	Techno-complex	Taxon*	Description of anthropogenic traces	Weight in gram	gL (mm)	gB (mm) highlighted in yellow, objects used to determine the width average of the ribs	Reference	Interpretation: pre-form or tool
Fig. 7 A	HF 28	867	7	IV	Aurignacian	megafaunal-size	Transverse groove just on one side (medial) of the compacta close to the ventral end of the rib, at the other end a straight natural break with modern damage	32,0	165,0	28,9 (complete rib width)	This paper	
Fig. 7 B	HF 55	671+672	3BL	IIB	Gravettian	megafaunal-size	Split rib used as punch, spongiosa shows grooves from splitting (s. close-up), impacts were not placed along the edge, but in the Sulcus costae	18,0	153,2	19,0	Barth 2007, Abb.36.5	punch or chisel
Fig. 7 C	HF 57	2600	3CF	IICF	Gravettian	megafaunal-size	Rib fragment with transverse groove in the spongiosa (arrow), however, splitting process was unsuccessful	18,7	94,8	32,5 (nearly complete rib width)	This paper	
Fig. 7 D	HF 56	1213+1226	3C	IIC	Gravettian	megafaunal-size	Transverse groove on the compacta with a tongue-shaped break caused by bending	1,2	47,0	12,3	This paper	
Fig. 8 A	HF 28	338	3C	IIC	Gravettian	megafaunal-size	Ventral rib end stripped off after splitting, creating a tongue-shaped end	12,6	67,3	36 (complete rib width)	This paper	
Fig. 8 B	HF 66	671	3C	IIC	Gravettian	megafaunal-size	Rib half with impacts from splitting the rib in the medio-lateral direction to create a pre-form for a point	39,0	153,0	18,9 (measured medio-lateral)	This paper	pre-form point
Fig. 8 C	HF 98	694+708	3D	IID	Gravettian	megafaunal-size	Split rib segment in cranio-caudal direction, very flat spongiosa. Transverse groove from splitting (arrow). The upper end is rounded and looks as if it was used, pre-form for a smoother	37,7	147,2	33,4	This paper	pre-form smoother
Fig. 9	HF 100	994+995	3CF	IICF	Gravettian	megafaunal-size	Impacts along the edges from splitting. The spongiosa is very flat and shows grooves from splitting (see arrows), pre-form for a smoother	63,9	220,0	31,9 (complete rib width)	This paper	pre-form smoother
Fig. 10 A	HF 58	484			collapsed profile below GH 3b	megafaunal-size	Rib used as a punch, with splintering at the upper and lower ends. The piece was produced from a quarter of a rib. Red arrow indicates an impact from splitting with a pointed tool. Pre-form point and/or punch/chisel)	31,7	174,0	19,9 (Quarter of the rib)	This paper	pe-form point used as punch/chisel
Fig. 10 B	HF 78	642+775	3C+3B	IIC+IIB	Gravettian	horse/bear-size	Heavily used complete smoother	18,3	151,5	25,4	Barth 2007, Abb.36.1	smoother
Fig. 10 C	HF 57	2695	3CF	IICF	Gravettian	megafaunal-size	Broken point, the compacta on both long edges is very close, the rawform of the point was produced by medio-lateral splitting of the rib	12,1	96,3	12,7	This paper	point fragment
Fig. 10 D	HF 89	468	3C	IIC	Gravettian	megafaunal-size	Impacts on the long edges from splitting, both ends are splintered on compacta and spongiosa side, use as punch or wedge very probable	22,2	99,9	35,2 (complete rib width)	This paper	punch/chisel/wedge
Fig. 10 E	HF 31	2656	7AA	VAA		megafaunal-size	Smoother, heavily used. No visible impacts, but a longitudinal groove is present on the compacta (see arrow) from dissecting the rib into quarters	12,9	123,4	19,7	This paper	smoother

*** (megafaunal size = mammoth-/rhino-sized)**

Figures in the Suppl.	Site and Square	ID	GH	AH	Techno-complex	Taxon*	Description of anthropogenic traces	Weight in gram	gL (mm)	gB (mm) highlighted in yellow, objects used to determine the width average of the ribs	Reference	Interpretation: pre-form or tool
Suppl. 1 A	HF 65	1306	6A	IIIa	Aurignacian	megafaunal-size	This rib segment or rib blank shows straight breaks on both ends; the upper end probably has a transverse groove (not visible in the photo) and the lower end a tongue-shaped break. This piece shows the full length of a segment (raw form), prepared for further processing	56,3	133,5	34,7 (complete rib width)	This paper	rib blank
Suppl. 1 B	HF 59	1133	3BL	IIB	Gravettian	megafaunal-size	Both long edges show impacts from splitting, but the pointed tool was placed not at the outermost edge, but toward the inside, where the compacta is thinner. Transverse grooves on the spongiosa are visible (see arrows). In addition, both ends have splintering from the use as punch	57,5	230,4	31,7 (complete rib width)	This paper	punch/chisel
Suppl. 1 C	HF 57	1978	3CF	IICF	Gravettian	megafaunal-size	Impacts along both long edges, a transverse groove from splitting starts at one of the impacts (see close-up), use of an antler tine very probable	13,0	86,5	26,5 (complete rib width)	This paper	pre-form smoother
Suppl. 2	HF 66	583	3C	IIC	Gravettian	megafaunal-size	Impacts along both edges (eight on the thinner compacta side and three on the thicker compacta), transverse grooves visible on the spongiosa (arrows), tongue-shaped breaks at both ends	56,0	180,0	34,4 (complete rib widthe)	This paper	pre-form smoother
Suppl. 3 A	HF 30	401	3C	IIC	Gravettian	megafaunal-size	Impacts from splitting process visible, spongiosa very smooth and flat, straight breakage at the upper end	33,5	115,3	37,1 (complete rib width)	This paper	smoother
Suppl. 3 B	HF 77	1533	3CF	IICF	Gravettian	megafaunal-size	Large tongue-shaped break at the lower end, probably caused by bending, no transverse groove visible, impacts along the edge, but no splitting	18,7	89,5	26,2 (complete rib width)	This paper	
Suppl. 3 C	HF 79	1842	3CF	IICF	Gravettian	megafaunal-size	Impacts from splitting placed in the sulcus costae, at the lower end a tongue-shaped breakage	51,1	120,4	35,0 (complete rib width)	This paper	
Suppl. 4	HF 56	2459	3CF	IICF	Gravettian	megafaunal-size	Rib segment naturally eroded at the upper end, tongue-shaped break at the lower end, numerous cut marks on the lateral side of the corpus, but no impacts	94,7	250,0	39,1	This paper	
Suppl. 5 A	HF 100	618	3C	IIC	Gravettian	megafaunal-size	Ventral rib end with cut marks. The upper end has a tongue-shaped break without traces of a groove. Both longitudinal edges have a natural platform to hold a pointed tool. The tongue-shaped end is splintered on both faces (compacta and spongiosa side), probably this end was used as punch or chisel	41,2	116,4	27,6 (complete rib width, measured at the corpus)	This paper	punch/chisel
Suppl. 5 B	HF 66	1430+1559	3CF	IICF	Gravettian	megafaunal-size	Pre-form for a point, splitting in medio-lateral direction, visible are several impacts along the thinner compacta side	19,8	160,0	13,4 (measured medio-lateral)	This paper	pre-form point
Suppl. 5 C	HF 28	958.1	0-3B	-IIB	collapsed profile	megafaunal-size	Pre-form of a point, dissection in medio-lateral direction alongside the rib	11,7	123,8	20,9	This paper	pre-form point
Suppl. 5 D	HF 100	918	3C	IIC	Gravettian	megafaunal-size	Half-product of a point, no impacts visible from splitting, because the long edges are reworked and scraped with a lithics	18,1	122,7	16,5	This paper	half-product point

Table 2. (continued)

Suppl. 6 A	HF 86	127	3BL	IIB	Gravettian	megafaunal-size	Heavy adze-shaped strokes from splitting the rib medio-laterally, the lower end shows splintering. The piece was either used as punch/chisel, but might be also a pre-form for a point	43,1	200,0	23,2	This paper	pre-form point used as punch/chisel
Suppl. 6 B	HF 55	835+855	3C	IIC	Gravettian	megafaunal-size	Impacts along the edges, tongue-shaped breaks at both ends	14,0	125,4	31,0 (nearly complete rib width)	This paper	
	HF 65	928						8,6	see above			
Suppl. 6 C	HF 58	810	3C	IIC	Gravettian	megafaunal-size	Rib piece is split and quartered, has a very straight broken end, shows polish as if it was used as a smoother	18,0	91,0	22,3 (Quarter of the rib)	This paper	use as smoother (?)
Suppl. 7 A	HF 68	1990	3CF	IICF	Gravettian	megafaunal-size	Two impacts are visible along the edge, splitting in cranio-caudal direction occurred not directly at the edge, but slightly above it	53,4	136,0	36,8 (nearly complete rib width)	This paper	pre-form smoother
Suppl. 7 B	HF 26	337	3DA	IIDA	Gravettian	megafaunal-size	Punch, rib split medio-laterally, splintered out at both ends	13,3	69,6	17,0 (rib measured cranio-caudal)	This paper	punch
Suppl. 7 C	HF 58	1141	3CF	IICF	Gravettian	megafaunal-size	Impacts along both long edges, multiple cut marks on the lateral side of the corpus, tongue-shaped breaks from bending and breaking the rib at both ends	26,0	131,4	26,0	This paper	pre-form smoother
Suppl. 7 D	HF 101	343	3C	IIC	Gravettian	megafaunal-size	Split piece of rib in cranio-caudal direction with nice impacts at the long edges, spongiosa very flat	32,7	142,4	27,7 (complete rib width)	This paper	pre-form smoother
Suppl. 8 A	HF 67	1622	3CF	IICF	Gravettian	megafaunal-size	Split rib into halves, transverse incisions on the rib compacta (possible decoration) were cut by dividing the rib into quarters. Splintering at both ends is visible, usage as a punch/chisel likely	10,7	90,1	17,3	This paper	punch/chisel
Suppl. 8 B	HF 78	1143	3CF	IICF	Gravettian	megafaunal-size	Rib split into halves by knapping or chiseling along the edge, then quartered and used as punch or chisel	13,6	118,6	19,7	Barth 2007, Abb. 53	punch/chisel
Suppl. 8 C	HF 77	672	3C	IIC	Gravettian	megafaunal-size	Smoother, heavily used, with incisions on the medial side of the rib, evidence of 3 impacts along the edge still visible	11,6	105,6	19,8	This paper	smoother
Suppl. 8 D	HF 79	1969	3CF	IICF	Gravettian	megafaunal-size	Split rib, splintering on the upper end visible on the compacta and on the spongiosa face, usage as chisel or wedge	20,8	84,3	28,0 (complete rib width)	This paper	chisel/wedge
Suppl. 8 E	HF 25	136	3CF	IICF	Gravettian	megafaunal-size	Smoother completely worked on all surfaces. One side has an incised decoration. Traces from splitting the rib are not any more visible	38,6	165,0	Width 23,6, Thickness 10,5	Barth 2007, Abb. 52.5	smoother
Suppl. 9 A	HF 67	1893+1940	3CF	IICF	Gravettian	megafaunal-size	Fragment of a point, evidence of medio-lateral dissection of the rib	12,2	130,7	12,2	This paper	point fragment
Suppl. 9 B	HF 88	504	3CF	IICF	Gravettian	megafaunal-size	One impact at the long edge from splitting is visible, all sides are completely reworked (scraped), the rib was split medio-lateral, since the original compacta is visible on both sides	8,7	73,4	Width 17,6, Thickness 7,5	Barth 2007, Abb. 52.6	point fragment
Suppl. 9 C	HF 76	409	3BL	IIB	Gravettian	megafaunal-size	Fragmented point made of a split rib	7,6	67,0	13,3	This paper	point fragments
	HF 79	1495	3C	IIC				3,3	38,0	13,3		
Suppl. 9 D	HF 67	1544+1563 +1569	3C	IIC	Gravettian	megafaunal-size	Impacts on both long edges. The rib broke into 3 pieces, thus splitting was unsuccessful	23,4	121,3	35,0	This paper	
Suppl. 10	HF 77	418	3C	IIC	Gravettian	Mammoth	Removal of the rib head, scaping of the surface with incisions on the medial side of the corpus (deco?), knapping to split the rib, however, splitting unsuccessful	84,9	196,0	34,3 (complete rib width)	This paper	
Suppl. 11	HF 79	2537			no layer	megafaunal-size	Impacts along both long edges placed in the sulcus costae, cut marks on the medial side of the corpus, tongue-shaped break at the upper end from bending. Splitting process not completed	71,9	167,0	38,3	This paper	
Suppl. 12	HF 57	2045	3CF	IICF	Gravettian	Mammoth	Strong proximal rib of an adult mammoth smashed with several strokes, carnivore gnawing at the proximal end	97,0	144,8	45,3	This paper	
	HF 100	725	3C	IIC				212,9	182,0	88,7		
Suppl. 13 A	HF 27	271	3BF	IIBF	Gravettian	megafaunal-size	Several impacts from splitting along the edge, impacts more likely from a chisel than from a pointed tool, rib was also quartered	32,7	190,0	26,0 (quarter of the rib)	This paper	
Suppl. 13 B	HF 68	1476	3CF	IICF	Gravettian	megafaunal-size	Likely knapping along the edge. Splitting the rib was not successful, however it was quartered and used as punch	19,0	120,2	26,3	This paper	punch
Suppl. 13 C	HF 68	1867	3C	IIC	Gravettian	megafaunal-size	One very pointed impact at the edge from splitting is visible, a tongue-shaped break at the lower end	19,0	75,9	35,1 (nearly complete rib width)	This paper	
Suppl. 14	HF 57	1374	3CF	IICF	Gravettian	Mammoth	Rib head of a young mammoth with 3 adze/chisel shaped strokes to remove the head from the corpus, carnivore gnawing visible at the proximal unfused articulation	46,0	78,7	68,7	This paper	

*** (megafaunal size = mammoth-/rhino-sized)**

Structure and Implementation

The participants in the workshop were undergraduate and graduate students at the University of Tübingen. At the beginning of the workshop, they received an introduction into the archaeological and archaeozoological background of the Ach Valley caves. Archaeological material, such as osseous points and smoothers, but also discarded mammoth rib fragments with anthropogenic modifications from Geißenklösterle (Conard & Malina, 2003; Hahn, 1988) and Hohle Fels (Conard, 2002; Conard & Janas, 2018; Conard & Malina, 2007, 2010, 2019; Conard & Uerpmann, 1999; Conard & Wolf, 2020) were shown to the participants of the workshop for study. The displayed archaeological material included the pieces depicted in Figs. 7, 8, 9 and 10 and in the Supplementary Figures S1-S14.

The workshop included 10 students who were divided into five teams of two people each and one team of three supervisors. One person conducted the experimental work on the rib, the second person documented the work with a protocol and photos, and then they exchanged roles. Each team chose a rib with an especially long and straight rib corpus. The aim of the experimental work was a) to produce a rib segment, b) to split the rib segment and c) to shape the split segment into a form resembling a Gravettian smoother or point.

As the experiments were explorative, the participants were not obliged to follow a specific protocol; however,

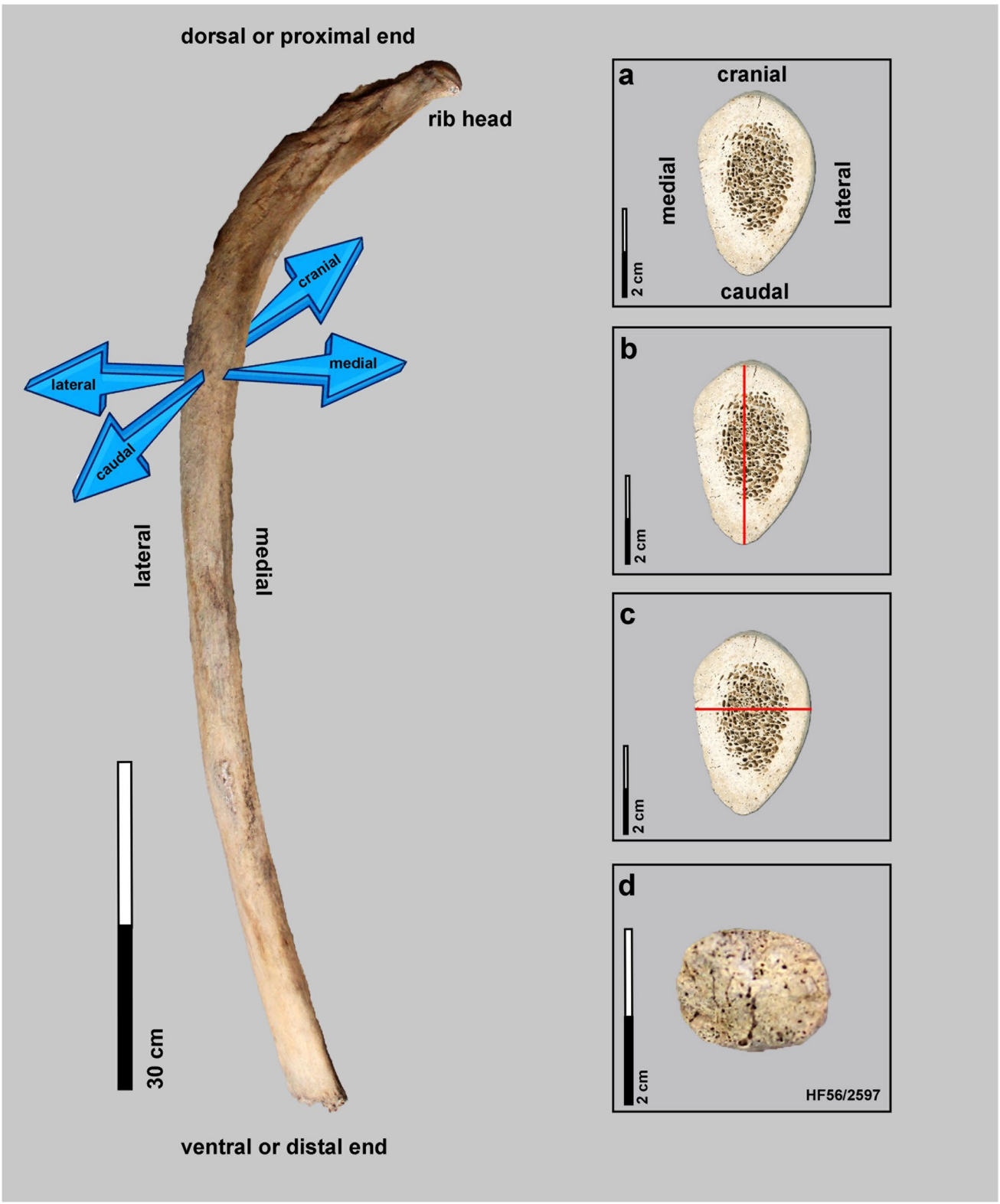


Fig. 3 Orientation and nomenclature of a rib, 4th left Molly rib, view from caudal, **a**) Cross section of a mammoth rib. **b**) Cranio-caudal transection of a mammoth rib, the red line indicates where it would be split to manufacture a smoother. **c**) Medio-lateral transection of a mammoth rib, the red line indicates where it would be split to manufacture a point. **d**) Cross section of a broken Gravettian bone point (HF 56/2597) showing the typical spongy compacta of a mammoth rib (Photo: A. Blanco-Lapaz)

they had to note down each step of the process. Each team could directly exchange their experience with other teams.

Production steps

The workshop followed three production steps:

A. Producing rib segments
B. Splitting rib segments
C. Manufacturing tools

Without designing a tight protocol for the workshop, we trusted in the ability and creativity of the participants to find a solution. The protocols and documentation of the teams were evaluated and summarized. Patterns in the working procedures of the teams were noted and form the basis of this article.

A major result of the workshop is the description of the work and experience of the teams. Our next step was to compare the results with the archaeological evidence. As we outline below, some results are directly comparable with athe archaeological material, and others are not.

Results

Results of the Workshop

Producing a Rib Segment At the beginning, most teams defined the length of a segment on the rib. Then either, a transverse groove on the medial (flat) side or on the lateral (domed/convex) side of the rib was incised with a transverse groove ('Querrille'), in most cases a groove around the whole corpus like an annular notch ('Ringkerbe') was produced by six teams (see Fig. 4 A, B, C).

Most teams produced two annular notches in order to access a segment of the rib corpus. The purpose of this exercise was to create a straight platform at the proximal or distal end of the segment as a basis for vertical splitting. The proximal (or dorsal end) and/or distal (or ventral end) part of the rib was then removed (see Fig. 3 for orientation and nomenclature). Despite the predetermined breaking line by the transverse groove or annular notch, all teams used brute force to initiate the final break. Some



Fig. 4 Workshop: Creating a rib segment. **A**-**C**) Cutting a transverse groove with a flint flake. **D**) Breaking the rib with a hammerstone. **E**) Broken rib. Note the whitish, dry fat inside the compacta. **F**) Tongue-shaped break, after preparing a transverse groove. Photos: B. Schürch and L. Brunke. Plate: B. Schürch

used large hammerstones, others jumped on the ribs that had been placed on an anvil or large stone (Fig. 4 D). The reason for this was that, in the three years of maceration in the sediment, the ribs had developed whitish dried fat or grease in the cancellous bone, causing them to become sticky and brittle (Fig. 4 E). In addition, very often the break was not straight, but had a tongue-shaped fracture edge (Figs. 4 F and 5 E, F).

Three teams took another approach by removing the rib head first. This was based on a rib head from Hohle Fels (Suppl. Fig. S14) from a young mammoth (unfused *Facies articularis*). The piece preserves at least three heavy transverse adze-shaped strokes below the rib head from the dissection of the rib corpus. However, during the experiment the removal of the rib head was difficult to accomplish, even by repeated heavy strokes, and again brute force was needed to remove the rib head.

For both methods, either producing a segment with two annular notches or removal of the rib head using one annular notch, the assumption was made that a straight end or platform is needed to vertically split the rib segment. As discussed below, this assumption proved to be incorrect.

Splitting the Rib Segment Five teams initially tried to split the rib segment vertically, similar to lithic knapping that produces flakes or blades (e.g., Hahn, 1991; Pétillon & Ducasse, 2012). However, it became clear that vertical splitting was not possible, as cracks radiated from the axis despite grooves that participants manufactured in advance on the long side of the segments (see below, grooves as a 3rd method for splitting). This circumstance indicated that due to the different material properties of bones, including the fact that it is not as homogenous as flint, it behaves differently under such mechanical stress.

Since vertical splitting was not possible, all teams changed to a splitting strategy that involved going step-by-step along the length of the rib segment horizontally (Fig. 5 C, D).

Four different methods were applied by the participants to split the rib segments in this way:

1) Three teams knapped or flaked along the long edges (cranial or caudal side) with a hammerstone to access the spongiosa. This method was only successful on the caudal edge, since the rib is flatter on the caudal side and the compact bone is thinner.



Fig. 5 Workshop: Splitting the rib. **A**) Attempting to split the rib with a flint flake placed in the groove along the edge. **B**) Placing an antler tine into the groove in order to split the rib. **C**) Splitting the rib with an antler tine and keeping the rib halves apart with a lithic wedge. **D**) Traces of the antler tine after splitting. **E**) Typical grooves in the spongiosa of the rib halves after splitting. **F**) Removal of the ventral end of the rib, resulting in a tongue-shaped break. Photos: B. Schürch and L. Brunke. Plate: B. Schürch

2) Six teams ground one or both long edges on a sandstone slab until the spongy bone was visible. The grinding created a platform, on which wedges or antler tines could be placed to penetrate the segment by hitting into the inner part of the rib. Additionally, four teams deepened the grinded platform with a groove for better access. This was followed by inserting wedges or chisels for splitting.
3) A third method was applied by six teams to create lengthwise grooves along the edges of segments. These grooves served as a hold for wedges and/or antler tines to penetrate into the spongiosa.

   A variant was to place these grooves on the *Sulcus costae*, a natural depression along the rib body, with the advantage of a thinner compacta to penetrate in this part of the rib.

4) Two teams attempted a fourth method to open the long edge. They placed a row of holes with an antler tine (Fig. 5 D) on the *Sulcus costae* or another natural depression without grinding or grooving beforehand.

In general, it was always more effective to open both longitudinal edges of the rib. However, opening the rib segment lengthwise on one long side and then breaking it apart into two halves was also successful.

One or two teams left the ventral natural distal end of the rib unsplit, but eventually had to remove it in order to get two halves (Fig. 5 E).

Regarding the tools used to penetrate the spongy bone and split the segments, antler tines (Fig. 5 B, C) and chisels made of deer metapodials worked very well, because they got deep enough into the spongiosa and they were elastic. Flint wedges, lithic chisels or splintered pieces of any shape and size did not penetrate deep enough (Fig. 5 A); they splintered immediately into small fragments. All four methods of splitting a rib with antler tines or chisels left unambiguous traces by grooves inside the spongiosa (Fig. 5 E).

Another important observation was that the fissure must be kept open during the whole splitting process by wedges of any kind and material (Fig. 5 C).

Participants found that during the whole process the fissure between the two halves had to be kept open with wedges while splitting occurred (Fig. 5 C). Wedges of all materials worked to keep the fissure open and the wedge material itself did not influence the process.

Independently of the splitting method, sometimes cracks developed. These cracks did not follow the intended direction of the split, but went onto the surface of the rib body (Fig. 6 C). The same problem arose when wedges were inserted into the open split.

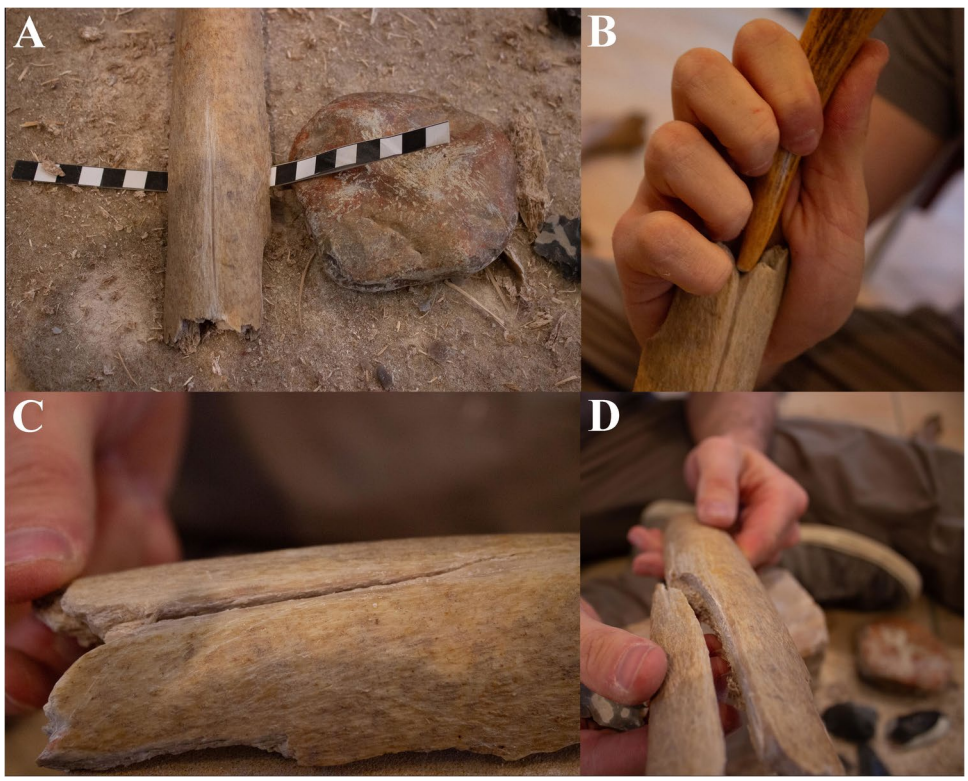


Fig. 6 Workshop: Producing a raw form for a point. **A**) Longitudinal groove in the middle of a rib half in order to split the rib into quarters. **B**) Attempting a vertical split with an antler tine in order to quarter the rib half. **C**) Split not following the groove, resulting in a short raw form for a point (**D**). Photos: B. Schürch and L. Brunke. Plate: B. Schürch

Manufacturing Tools After splitting the rib segments in cranio-caudal direction the raw form for a smoother is almost accomplished. Two teams removed the uneven spongiosa with a chisel. Thereafter the raw forms were shaped on a sand stone slab.

The raw form for a point was processed by placing a groove in the middle of one rib half (Fig. 6 A, B) in order to split it into a quarter of the rib using an antler tine or chisel. Some teams also used discarded pieces that resulted from previous steps of the process and seemed appropriate as a raw form for a tool (Fig. 6 D). Four teams then shaped the blanks on sandstone slab.

The intended length for smoothers and points was as long as possible, but often the full length was not achieved, due to incidental earlier breakage. The workshop products achieved the following measurements and vary considerably:

1) the rib segment halves reached a length of 110—515 mm and a breadth of 41.5–73.6 mm,
2) the raw forms for tools reach a length of 60–330 mm and a breadth of 15.5–60 mm,
3) the tools reach a length of 70–190 mm and a breadth of 19–52 mm.

Our next step was to compare the traits produced during the workshop with those on the archaeological material and vice versa.

Results—Application of Experimental Results to the Archaeological Material

The archaeological rib material of mammoth and of those in mammoth-/rhino-size preserve evidence of impacts and hacking executed to dissect the ribs, though the way people did this archaeologically is unknown. The workshop provided some analogous damage patterns to help us analyse the archaeological material. However, in some cases, there were clear deviations between the workshop and the archaeological reality of tool production.

The comparison follows the 3 main production steps of the workshop.

Producing Rib Segments So far, in the archaeological material, we identified only two instances of transverse grooves on one side of a rib (Fig. 7 A, D, see arrows) to section the rib with subsequent breaking.

However, tongue-shaped breaking edges could be evidence of breaking the rib without transverse grooves (Fig. 8 A and Suppl. Fig. S1 A). For example, the rib segment on Suppl.

Fig. 7 Hohle Fels ribs: **A**) Transverse groove on only the medial compacta side (arrow), close to the ventral end of the rib. The opposite end displays a straight break with modern damage. **B**) Split rib used as a punch/chisel, spongiosa shows grooves from splitting (see close-up). Impacts were not placed along the edge, but in the *Sulcus costae*. **C**) Rib fragment with transverse groove in the spongiosa (arrow), however, splitting process was unsuccessful. **D**) Transverse groove on the compacta (arrow) with a tongue-shaped break caused by bending. Photos: B. Schürch and S. Wolf. Plate: B. Schürch

Fig. S1 A shows straight breaks on both ends, on the lower end combined with a tongue-shaped break. There are several examples of clear straight dissections without visible anthropogenic traces on one end of the rib, combined with a tongue-shaped breaking edge (Suppl. Fig. S3 B). In the workshop we also experienced tongue-shaped breaks even after preparing a transverse groove (Fig. 4 E, F).

Splitting Rib Segments in Cranio-Caudal Direction The traces along the long edges of the mammoth ribs show notches, which we first interpreted as knapping in order to get access to the spongiosa. In some cases, the notches observed on the archaeological specimens might have been from knapping with pebbles or hammerstones. However, further analysis showed more delicate traces on most of the pieces (Suppl. Fig. S2; Suppl. Fig. S7 D). These traces were likely produced with pointed tools, such as antler tines or chisels, because the impact marks along the edges of the archaeological ribs are too small to be produced by larger artefacts like pebbles or hammerstones.

Traces of grooving or grinding the long edges, the methods 2 and 3 which we applied in the workshop, were not found on the Gravettian rib material. Rather, the ribs were opened just with the help of a pointed long tool (e.g., antler tine) through percussion, probably on the *Sulcus costae*. This is similar to the 4th method applied in the workshop.

This suggestion is supported by grooves on the inner spongiosa of the Gravettian ribs, which are likely traces from pointed longitudinal tools used during the splitting process by holding the rib segment in horizontal position (Fig. 7 B (see close-up), C; Fig. 9 (see arrows); Suppl. Fig. S1 B (arrows)).

Manufacturing Tools After splitting the rib segments in cranio-caudal direction the raw form for a smoother is almost accomplished. In the workshop the raw forms were shaped on a sand stone slab.

However, for the shaping of organic tools by grinding we have no evidence in the Gravettian material. Palaeolithic shaping was exclusively conducted by cutting and scraping with lithic artefacts (Barth, 2007).

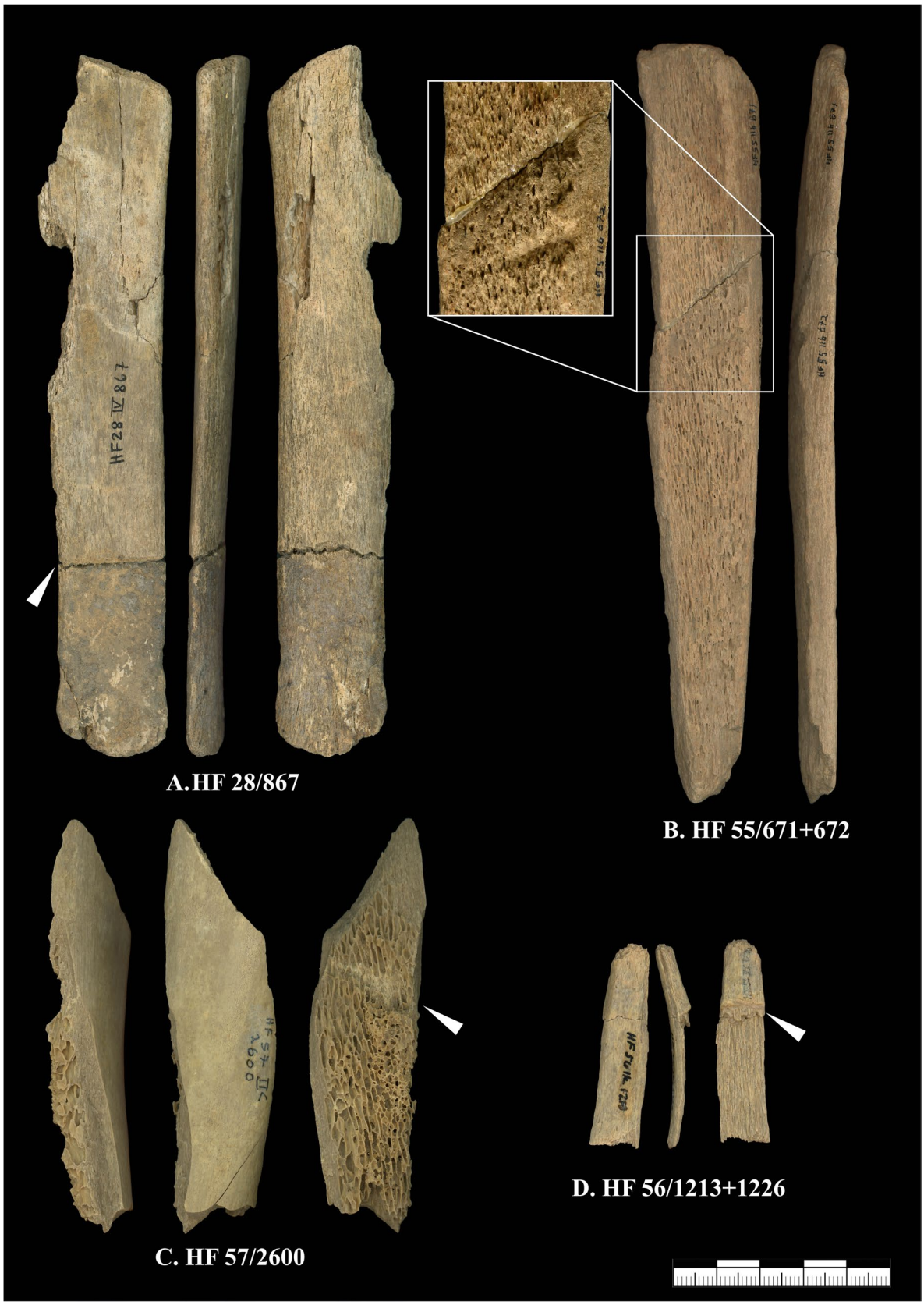

A.HF 28/867
B. HF 55/671+672
C. HF 57/2600
D. HF 56/1213+1226



Fig. 8 Hohle Fels ribs: **A**) Ventral rib end stripped off after splitting, creating a tongue-shaped end. **B**) Rib half with impacts from splitting the rib in the medio-lateral direction to create a pre-form for a point. **C**) Split rib segment in cranio-caudal direction, very flat spongiosa. Transverse very shallow groove from splitting (arrow). The upper end is rounded and looks as if it was used, pre-form for a smoother. Photos: B. Schürch and S. Wolf. Plate: B. Schürch



Fig. 9 Hohle Fels rib: Impacts along the edges from splitting. The spongiosa is very flat and shows grooves from splitting (see arrows), pre-form for a smoother. Photos: B. Schürch and S. Wolf. Plate: B. Schürch

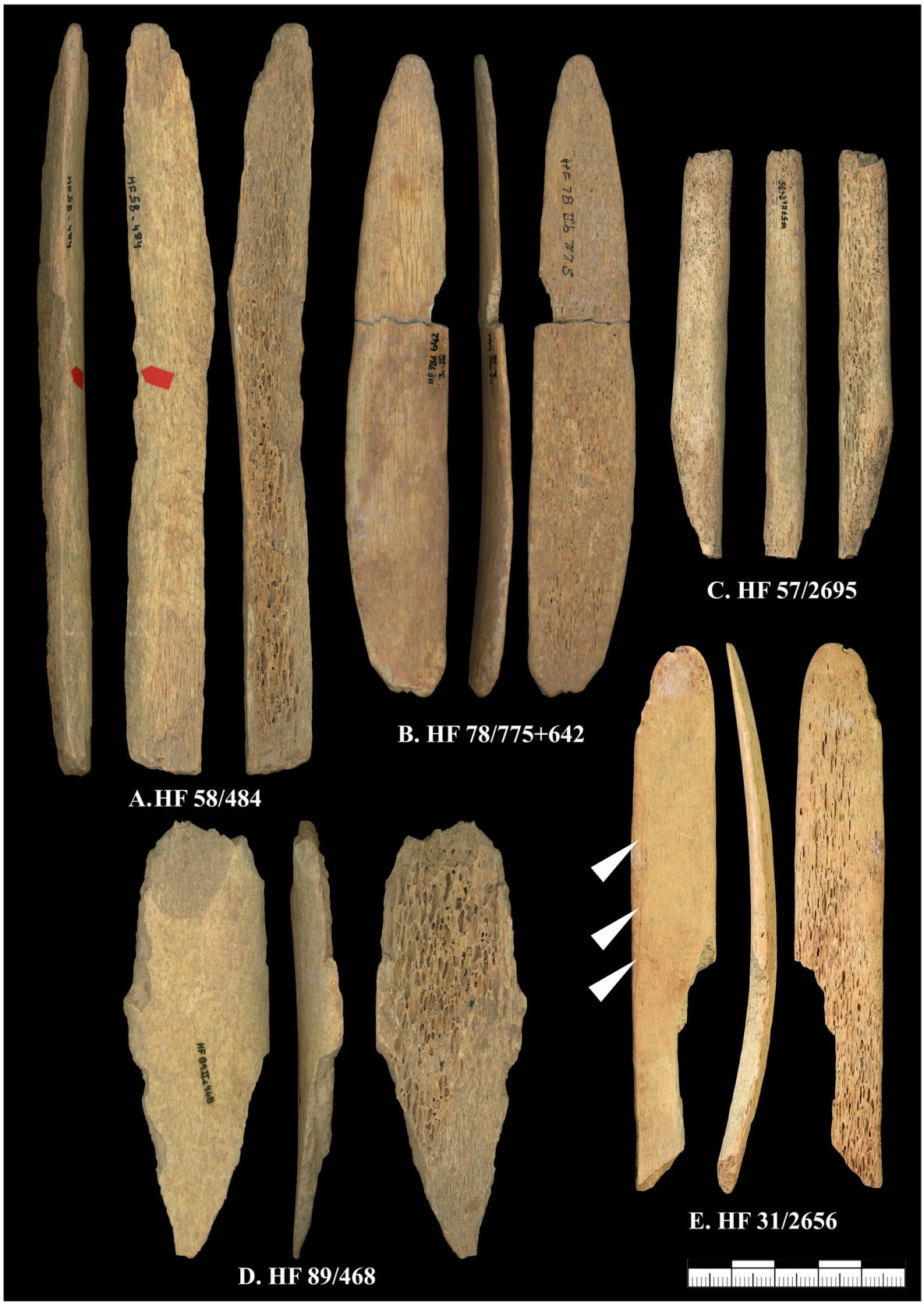

A. HF 58/484
B. HF 78/775+642
C. HF 57/2695
D. HF 89/468
E. HF 31/2656

Fig. 10 Hohle Fels ribs: **A**) Rib used as a punch, with splintering at the upper and lower ends. The piece was produced from a quarter of a rib. Red arrow indicates an impact from splitting with a pointed tool. Preform point and/or punch/chisel). **B**) Heavily used complete smoother. **C**) Broken point, with dense compacta on both long edges. The raw form of the point was produced by splitting the rib medio-laterally. **D**) Impacts on the long edges from splitting (arrows), both ends are splintered on the compact and spongy sides. Likely used as a punch or wedge. **E**) Smoother, heavily used. No visible impacts, but a longitudinal groove is present on the compacta (see arrow) from dissecting the rib into quarters. Photos: B. Schürch and S. Wolf. Plate: B. Schürch

For the manufacturing of points the members of the workshop placed a longitudinal groove in the middle of the rib half to produce a quarter of a rib. This kind of groove was recognized on one archaeological smoother (Fig. 10 E). In other cases, this trace of dissection might have disappeared following subsequent scraping and shaping the tools.

For the manufacturing of smoothers and points, it is important to consider the cross section of a mammoth rib (Fig. 3 B, C). There are two possible directions to bisect a rib corpus, namely a transection from cranial to caudal (see vertical red line in Fig. 3 B) or a transection from lateral to medial (see horizontal red line in Fig. 3 C). There is archaeological evidence for both directions in the mammoth rib material of Hohle Fels and Geißenklösterle.

Our suggestion is that bisecting the rib in the cranio-caudal direction served as pre-forms for smoothers (Figs. 8 C and 9; Suppl. Fig. S1 B, C; Suppl. Fig. S2; Suppl. Fig. S3 A; Suppl. Fig. S7 A, C, D) and the medio-lateral sectioning as pre-forms for points (Figs. 8 B and 10 A; Suppl. Fig. S5 B, C; Suppl. Fig. S6 A; Suppl. Fig. S13 A). In this way, the properties of the rib are best suited for the corresponding tool type.

Concerning the first step, producing a rib segment, we found only two examples of transverse grooves, but several 'combined' breakage edges. Namely, a straight broken edge on one side (medial or lateral) of the rib combined with tongue-shaped edge on the other side (medial or lateral). While the straight broken side looks like an old, dry break, the tongue-shaped side is evidence for a 'fresh' consistency of the bone. Therefore, we include these breakage pattern as anthropogenic modifications. It is very likely that transverse breaking was possible without grooves ("Querrille" or "Ringkerbe"), especially if we consider the use of juvenile mammoth ribs.

For the second step splitting the rib segment, we tried four different methods to dissect the rib in cranio-caudal direction. The fourth method, splitting by percussion with an antler tine, was the most successful and is closest to the archaeological evidence (Fig. 11). Traces of grooves or grinding were not observed in the archaeological context of the Gravettian.

Discussion and Interpretation

Looking back at the workshop, several aspects of our approach could be reconsidered. For example, we concentrated too much on splitting the ribs in a cranio-caudal direction, especially since we now recognize several examples in our archaeological material were people fractured the ribs by direct percussion in a medio-lateral direction (e.g., Fig. 8 B; Fig. S5 B, C; Fig. S6 A; Fig. S7 B; Fig. S9 A, B). However, it is not clear that this method would have been possible using the ribs that were available to us: large ribs from an old female elephant that we had previously buried for several years. Another important point is that through the study of the archaeological materials, we now recognize a third tool type made from ribs, specifically those that show splintering at both ends and likely used as some kind of intermediate tool (e.g., Fig. 10 A, punch or chisel).

Another important insight from the workshop is that the raw material we used did not correspond to the archaeological material in several aspects.

1) During the maceration process the bones became very dry and brittle, breaking like old wood, and the fat in the spongiosa became a sticky, fatty, white mass (Fig. 4 E). These circumstances hindered the experimental manufacturing of the ribs, which all participants noted. Areas with less or no whitish, dry fat could be handled more easily. This fits, too, with our taphonomic observations, that the archaeological bones were normally broken in a fresh or green state. Our interpretation is that Palaeolithic people used much fresher bones than what was used during the workshop, though we cannot comment on the timespan from the kill site to bringing the ribs to the cave and/or the length of their deposition, particularly during colder periods. It is clear, however, that no serious alterations took place before processing in the Palaeolithic.
2) Furthermore, the ribs came from smaller, probably younger animals with the exception of one rib, which reached the size of Molly's ribs. This rib showed anthropogenic impacts, the two parts were excavated in 3 m distance and later refitted (Suppl. Fig. S12). All other pieces in the Hohle Fels assemblage came from smaller or younger individuals. The average breadth of the mammoth ribs with anthropogenic modifications is 32 mm (see Table 2, highlighted in yellow), while the rib segments produced in the workshop were to 54 mm, a considerable size difference. This is especially noteworthy given that, though she was a fully adult cow of ca. 40 years, Molly was a female Asian elephant, and therefore not particularly large relative to other modern and Palaeolithic proboscideans. An age estimation of the

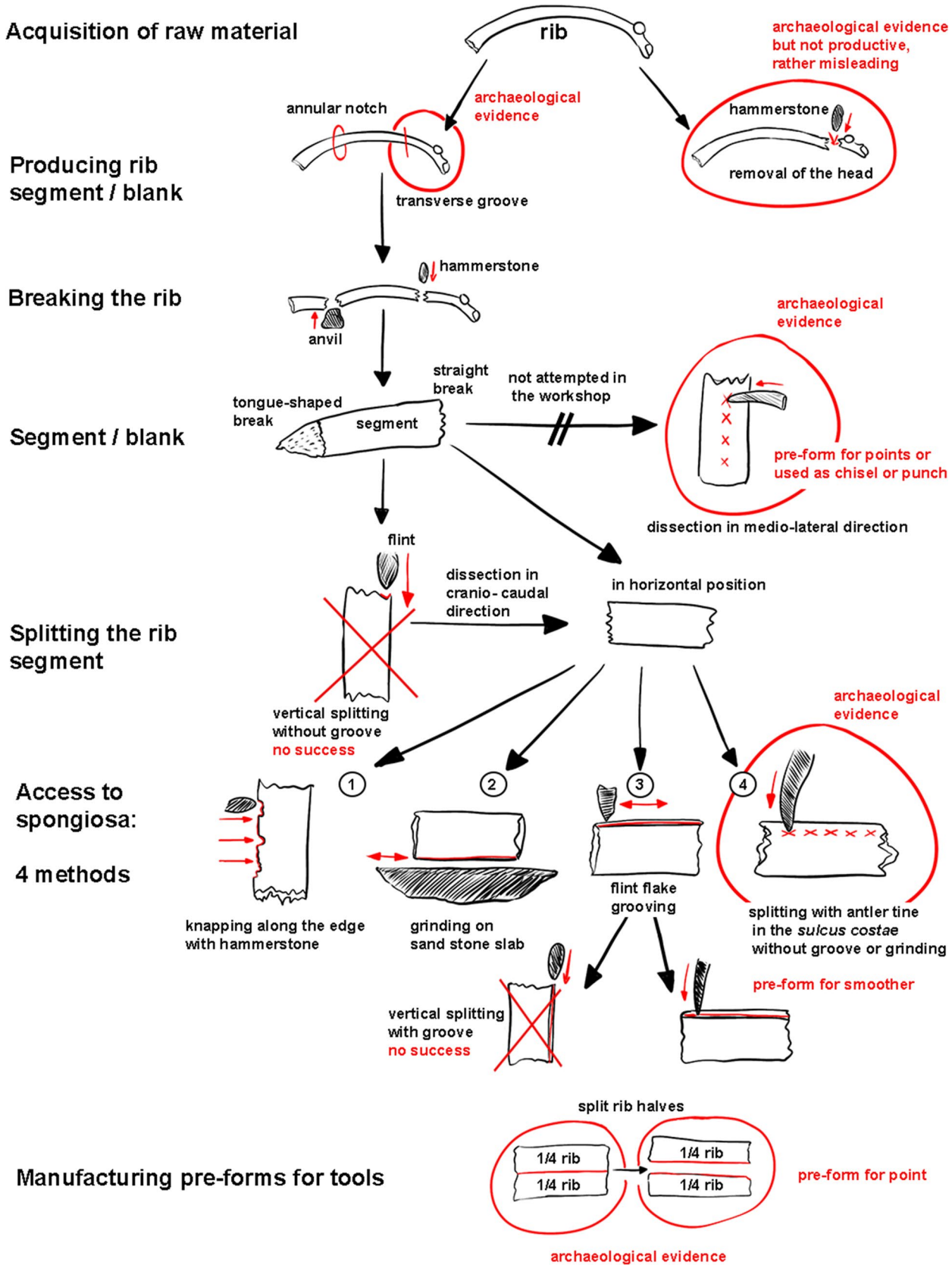


Fig. 11 *Chaîne opératoire* of processing proboscidean ribs during the workshop and its evidence in the archaeological record of the Ach Valley sites. Graphic: S. C. Münzel, F. Pretz and A. Blanco-Lapaz

manufactured mammoth ribs from Hohle Fels is difficult because mammoths are typically aged by their molar dentition corresponding with African Elephant Years (AEY) (Haynes & Klimowicz, 2015; Laws, 1966), and no other data for the postcranial elements of proboscideans are available. Just in one case at Hohle Fels, an open proximal rib epiphysis is present (Suppl. Fig. S14) pointing to a younger mammoth; the other remains are fragments of the rib corpus. Based on the size, however, it speaks for a selection of mammoth ribs towards smaller and/or younger animals. The mammoth remains of both caves, Hohle Fels and Geißenklösterle, include calves and yearlings (Münzel, 2004, 2005, 2019, pp 200) confirming a herd structure with juvenile individuals.

If these two points are considered, fresher material with more elastic property and rib material of juvenile or adolescent proboscideans, then our workshop has helped us understand the successful manufacturing of the bone tools made from mammoth ribs at Hohle Fels and Geißenklösterle.

Beyond Molly: Tools made from Megafaunal Ribs and other Experiments

Semenov (1964, p. 175) previously mentioned split mammal ribs used as so-called burnishers or smoothers at Kostenki I and Avdeevo in the Upper Palaeolithic of Russia; however, he did not describe their production.

Smoothers or burnishers date back to the Middle Palaeolithic and are known from sites like Salzgitter-Lebenstedt in Germany (Gaudzinski, 1999). The dominating elements at Salzgitter-Lebenstedt are mammoth ribs, fibulae and molars, which suggests the intentional selection of specific osseous materials (i.e., ribs and fibulae) for tool use. The Salzgitter-Lebenstedt assemblage is dominated by animals in age-group I, juveniles, indicating that ribs of younger individuals were chosen. Most of the unsplit and split ribs have pointed ends with anthropogenic modifications and use-wear. Along the edges of the split ribs, impacts are visible from the splitting process, a step of the *chaîne opératoire* which is also known from Upper Palaeolithic split rib tools. A multi-method use-wear analysis was recently performed on the Salzgitter-Lebenstedt materials, and confirmed hide-working activities of Neanderthals at the site (Robitaille & Gaudzinski-Windheuser, 2025). Furthermore, Middle-Palaeolithic sites in France, namely Pech-de-l'Azé I and Abri Peyrony, also revealed smoothers made from split and unsplit ungulate ribs (Soressi et al., 2013). However, Soressi et al. (2013) focused on use wear analysis on the tip of the tools, any traces of production are not mentioned.

So far, from the Swabian Jura, we have evidence of one Middle Palaeolithic smoother fragment made from a split mammoth-/rhino-sized rib from Fetzershaldenhöhle in the Lone Valley (Schürch & Conard, 2024) and another one from Große Grotte in the Ach Valley (Weinstock, 1999).

During the transition to the Upper Palaeolithic, an increasing number of archaeological sites yield smoothers made from mammoth-/rhino ribs. In particular, numerous Pavlovian tools from eastern Europe were manufactured from mammoth ribs and have been described from the sites of Pavlov I and Dolní Věstonice I (Barth, 2007; Brühl, 2005; Klíma, 1994). Rib tools are also known from the Austrian Gravettian, including the site of Willendorf II (Barth, 2007). In Bavaria, Weinberghöhlen has likewise preserved mammoth rib tools (von Koenigswald, 1974). Another split rib of mammoth-/rhino size derives from Wildscheuer (Lahn valley) and dates to the late Aurignacian (Kitagawa et al., 2025). Notches along the edge hint to the process of splitting the rib. Also, from Vogelherd, a mammoth-/rhino size smoother was recently dated to the Aurignacian (Schürch & Conard, 2026). In the Ach Valley, the caves of Hohle Fels, Geißenklösterle, Brillenhöhle and Sirgenstein (Hahn, 1977) yielded split mammoth ribs used as smoothers. The finds from Brillenhöhle were first mentioned by Riek (1973) and Otte (1981), who identified them as lissoirs or smoothers made from this raw material. Knecht (1991), in her dissertation on organic projectile points, discussed the Gravettian mammoth ribs from Brillenhöhle and Geißenklösterle, describing them as having been split by deep grooves worked into the lateral edges and ends before the fragment was divided (p. 388). However, we were unable to confirm such traces in our own examination of the faunal material from Brillenhöhle. Tools made from mammoth and mammoth-/rhino sized ribs are widely spread organic artefacts, however, the manufacturing of these artefacts remain fairly unexplored.

The archaeological experiments by Averbouh (2000) and Tartar (2009) referred to Upper Palaeolithic osseous assemblages from southwestern France. After making a circumferential notch on a rib, Averbouh (2000) fractured the rib by bending it, but she did not describe in detail how to split the rib. However, Tartar (2009) worked on the splitting process of ribs concerning the manufacture of smoothers. First, she studied the Aurignacian artefacts from Castanet-Nord, Brassempouy and Gatzarria, mainly made from ribs of bovids, horses and reindeer. She noticed scraping marks on the edges of some ribs or thinning of the edges until the spongiosa becomes visible. She noted that eleven artefacts from Brassempouy show no evidence of edge preparation by abrasion. Instead, they displayed irregular fracture surfaces, sometimes accompanied by depressions resembling percussion notches (Table 32, Plates III 1, 5, p. 11 and Plate IV 4, p. 13). These traits point to a second method of splitting, which involves preparing the edges by percussion, without

abrasion. This edge-retouching technique was identified by Voruz (1989) on Neolithic material. Tartar retraced both splitting methods in her experiments. She reported a groove along the lateral edges of rib artefacts, which was made to prepare the bone to be split. With the help of this procedure, the wedges for splitting can easily be inserted and the rib can be split successfully (Tartar, 2009, p. 78–79). The second method concerning percussion along the edges can be done by positioning the rib segment in two different ways. One option is to put it upright in transverse position on an anvil and strike the long edges with a cobble (Plate XIX 4, p. 45). This hypothesis was first proposed by Vézian and Vézian (1970, p. 59) to explain the splitting of ribs in the Early Aurignacian at La Tuto de Camalhot. Alternatively, the rib segment can be laid flat on the anvil and one or both edges are "retouched" with a cobble (Tartar, 2009, Plate XIX 5, p. 45). Also, Liolios (1999, p. 144) mentioned the retouching of rib edges for the Early Aurignacian at Geißenklösterle. Additionally, David (2004, p. 140) presented the same technique for Mesolithic rib artefacts from Ulkestrup I in the frame of her detailed descriptions of Mesolithic technologies. She also prepared the edges of the ribs by abrasion in her experiments in order to retrace the *chaîne opératoire* for Mesolithic objects (David, 2004, pp. 165–179). The splitting then proceeds in the same way for ribs whose edges were prepared by abrasion and for those whose edges were prepared by percussion (Plate XIX 6, p. 45).

Our observations on the mammoth rib material from the Swabian Jura are consistent with Tartar's work concerning the artefacts of Brassempouy, in which no preparation of the edges by abrasion took place. Tartar noted that splitting ribs by percussion is actually more frequently observed in the archaeological record of the sites Castanet-Nord, Brassempouy, and Gatzarria than the preparation of edges by abrasion. This technique was evidently already a common practice in the Aurignacian of southwestern France. For the artefacts from the Swabian Ach Valley sites, we were able to demonstrate this technique for the Gravettian on the basis of the mammoth rib artefacts and through our experimental work. Further research is required to examine the Aurignacian rib finds in greater detail. Such work could clarify whether, and in what ways, people contemporaneously handled ribs, also from different animal species in different regions.

Smoothers or burnishers made from split ribs are often interpreted as hide-working tools (e.g., Scheer, 1995; Averbouh & Buisson, 2003). In the archaeological record of other Palaeolithic sites, there are also complete ribs that could have been used in hide-working. However, the question remains as to why ribs were split when they were used for currying or tumbling raw hides as part of fur processing. According to Tartar (2009, p. 91–92), the splitting of ribs in the Aurignacian of southwestern France reflected a need for flexibility concerning the use of flatter ribs in general. Tartar's hypothesis should be tested through experiments. Also, use-wear analysis on the mammoth-rib tools from Swabia should be conducted.

Conclusion

An important requirement to study the *chaîne opératoire* of organic tools is a profound knowledge of the faunal remains of the respective site. Through the assessment of thousands of bone fragments over the years, rib fragments were eventually identified as the waste (or discarded) products of a manufacturing process, which had previously been unidentifiable in the archaeological record.

Through the experimental splitting of elephant ribs and our own experience, it was possible to reconstruct the method of splitting mammoth ribs in the Gravettian (Fig. 11). The split ribs served as pre-forms for smoothers and points as well as for chisels.

The ribs used for tool manufacture in the Gravettian of the Ach Valley had not been lying exposed on the landscape or stored for long, rather they were processed promptly. In addition to providing evidence for the selective transport of certain elements for tool manufacture, it also supports the idea that Gravettian people had primary access to mammoths, either through hunting or the immediate discovery of mammoth carcasses. Compared to the Asian elephant ribs used in the experiment, the archaeological ribs are smaller. We therefore conclude that they derive from younger animals, which were probably preferred as raw material for tool production.

Concerning the Gravettian artefacts of the Swabian Jura, we found no evidence of grinding or abrasion along the edges. We also doubt the retouching of the edges with a hammerstone to get access to the spongiosa for the artefacts from Hohle Fels and Geißenklösterle, because most of the traces are too delicate. We interpret them as punching with long pointed tools made from organic material. It was also observed that the spongiosa inside the rib halves showed transverse grooves from the splitting process. In a second step the rib halves were further divided into quarters to obtain smaller raw forms. It also became clear that tools made from organic raw materials are better suited for splitting than lithic tools. The tips of antler tines proved to be very efficient in the experimental approach. In addition to the previously known tool types of points and smoothers, chisels made from rib fragments could also be identified.

We already conducted subsequent exploratory workshops, for example to process raw skins. These experiments need to be repeated with a more formalized protocol

and combined with a study of use wear. Results from such experiments could then be compared with the archaeological record of the Swabian Jura in order to also understand the manufacture and use of smoothers/burnishers. We also plan future work with fresh and/or soaked ribs to overcome some challenges identified in the current study. There is also work to be done regarding use-wear on the tools used for splitting the ribs, such as antler tines, hammers, chisels, and lithics, and subsequent comparisons with archaeological materials.

In summary, the information gained from this experiment has sparked an entire research agenda that we look forward to initiating in the coming years. It is our hope that continued work will help answer many open questions regarding the use of mammoth and other taxa as part of the osseous industry during the Palaeolithic in the Swabian Jura.

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Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Competing interests The authors declare no competing interests.

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