Reviewed Article:

Innovative Osseous Technologies of the Early Upper Palaeolithic of the Swabian Jura – The Age of Ivory

Persistent Identifier: https://exarc.net/ark:/88735/10806

EXARC Journal Issue 2025/2 | **Publication Date:** 2025-08-06

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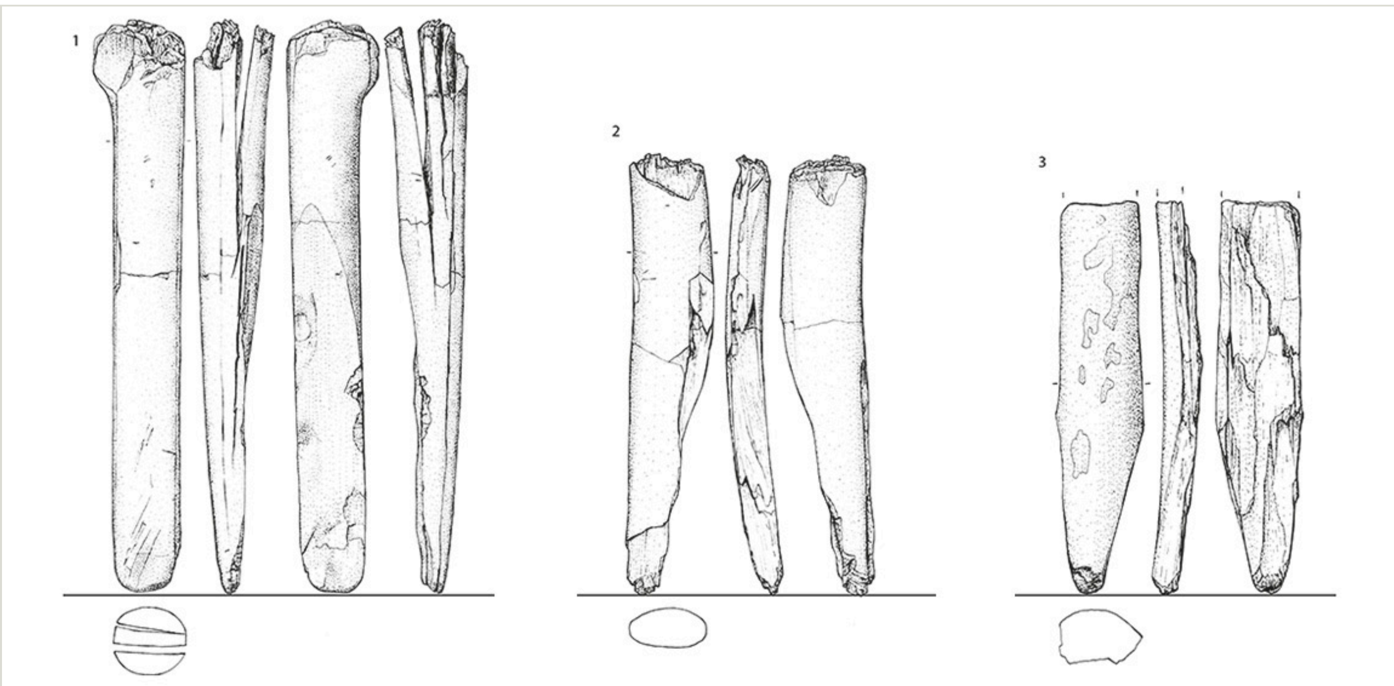

The Swabian Aurignacian is well known for its vast assemblages of functional and symbolic artefacts made from mammoth ivory. This contrasts with the Lower and Middle Palaeolithic technologies that contain sparse evidence for the manufacture and use of tools made from osseous materials. Only with the early Upper Palaeolithic did hominins begin to use ivory for a wide range of tools related to hunting and subsistence, and artefacts used in the symbolic sphere. This paper focuses on examples of bevelled artefacts made from mammoth ivory from the Hohle Fels and Geißenklösterle caves in the Ach Valley of the Swabian Jura (southwestern Germany) to reconstruct the ivory technologies used during the Aurignacian. With the help of an experimental approach, we tested four modes for using the bevelled artefacts. We found evidence that Aurignacian people most likely used these tools as chisels to work osseous materials.

> “Within a short time of use of these chisels, they worked off the edges with a great deal of effort. The question arises, why? Perhaps the end product was not as important as the action performed? Many questions still remain unanswered. We assume that such a tool could have been in use for multiple work steps, even after the proximal end was worn down.

Introduction

Lower and Middle Palaeolithic technologies contain sparse evidence for the manufacture and use of formal tools made from osseous materials (Leakey, 1971; Tromnau, 1983; Gaudzinski, 1999; Gaudzinski *et al.*, 2005; Soressi *et al.*, 2013; Baumann *et al.*, 2022; Tartar *et al.*, 2022). Although mammoths inhabited Eurasia since the Middle Pleistocene and their carcasses with their tusks were supposedly abundant on the landscape (Lister and Bahn, 1997; Kahlke, 2015; Boeskorov *et al.*, 2018; Vercoutère and Patou-Mathis, 2018), hominins only occasionally transformed this material into objects that were probably used as tools (Julien *et al.*, 2015).

Some of the few known ivory artefacts from the Middle Palaeolithic have turned out to be of natural origin (Villa and d'Errico, 2011). In Eurasia, humans began to exploit ivory systematically in the early Upper Palaeolithic (Riek, 1934; Hahn, 1988; Wolf, 2015; Pitulko *et al.*, 2016). Excavations in deposits of the Swabian Aurignacian have delivered numerous and diverse artefacts made from mammoth ivory, which are characteristic of this part of Central Europe (Riek, 1934; Hahn, 1986, 1988; Conard *et al.*, 2004, 2009; Conard, 2009; Wehrberger, 2013; Wolf, 2015; Wolf and Conard, 2015; Dutkiewicz *et al.*, 2018; Dutkiewicz, 2021; Conard and Rots, 2024) (See Figure 1).

Here we present an assemblage of mammoth ivory tools previously described as chisels, which was found in close association in the Aurignacian layer IV in Hohle Fels Cave near Schelklingen in the Swabian Jura, southwestern Germany (Conard and Malina, 2020). In 2019, the excavation team recovered three large elongated ivory tools in archaeological horizon IV, ranging in length between 13 and 22 cm. The tools come from a single feature (feature 6) with concentrations of burnt materials including burnt bone, char and charcoal with compacted sediments (Miller, 2015). All three artefacts preserve similar modifications to their proximal and distal ends. The ends of these artefacts have heavily battered surfaces.

Such battered surfaces have also been observed on other ivory tools from the Swabian Aurignacian (Wolf, 2015). Using experimental archaeology, our research questions were 1) if these tools could have served as chisels after testing different actions with modern replicas and 2) which actions caused the battered ends. We present results from our experimental approach and compare the observations from the original and experimental artefacts. These results demonstrate how Aurignacian people likely used these tools. In doing so, we gain new insights into an innovative ivory technology used for the first time by people in the Upper Danube region.

The raw material ivory

The majority of a tusk is comprised of dentine with an additional thin layer of cementum and a small cap of enamel at the pointed end (Sui and Cui, 1999; Locke, 2008; Heckel, 2018a; Pfeifer *et al.*, 2019; Baker *et al.*, 2020). As with other osseous materials, ivory is a composite biological material with an inorganic matrix of apatite and an organic matrix of collagen staple fibres, but it is particularly known for its density, toughness and strength relative to other hard tissues of animals. The unique structural features of tusks are essential for the optical identification of ivory and it has specific mechanical characteristics (Bonfield and Li, 1965; Heckel, 2009; Heckel and Wolf, 2014): the constituent materials of dentine are deposited by dentinal tubules, which extend out from the centre of the tusk, the nerve channel, to the interface between dentine and cementum. Saunders (1979) and Locke (2008) report the diameter of these tubules to be 5 μm; Espinoza and Mann (1993) published the diameter of 0.8 μm to 2.2 μm. The latter determination is based on SEM analysis of dentin from elephant, mammoth and mastodon tusks. The tubules are widest at their origin in the centre of the tusk and decrease towards the interface with the cementum. When the tusk is viewed in cross-section, these tubules extend like the spokes of a wheel into thin radial lamellae. These lamellae form one of the structural attributes that help identify ivory. At the individual level, they are not visible to the naked eye; but aggregations of lamellae are often visible on the ivory surface, and it is partly along the radial lamellae that ivory delaminates (Poplin, 1995) and debits (Heckel and Wolf, 2014). Ivory has an annual growth cycle (Fisher *et al.*, 2003) and dentin is deposited in the form of fine, interlocking cones, which appear as concentric rings in cross-section (Owen's Lines, [Owen, 1840-1845]). Ivory also disintegrates along the interfaces between these concentric cones. Radial lamellae with smooth surfaces are peculiar to ivory. Interfaces between growth layers and between radial lamellae, containing dentinal tubules, constitute zones of mechanical weakness conducive to the propagation of fracturing or splitting, as well as natural delamination over time (Poplin, 1995; Bonfield and Li, 1965; Heckel, 2009). The most recognisable macroscopic structural attribute of ivory is the diamond pattern formed by the Schreger Lines (Schreger, 1800). A number of explanations have been proposed for the origin of Schreger Lines. Some authors have noted that the alternation of lighter and darker bands is the product of sinusoidal undulations of the dentinal tubules (Miles and White, 1960; Saunders, 1979; Espinoza and Mann, 1993). Locke (2008) attributed Schreger's Lines to helical structuring of the radial lamellae formed by stiff dentinal tubules. Three-dimensional microscopic analyses were carried out by Virág (2012) on samples of 40 tusks from 5 different proboscidean species. These confirm that the undulating morphology of the dentinal tubules, as well as the causal relationship between these sinusoidal undulations and Schreger Lines. The unique structure of ivory produces a fracture pattern not seen on bone and antler. These are "step fractures" (terracing as proposed by Heckel and Wolf, 2014), created by propagation of fractures along the interfaces between the concentric rings formed by the growth layers and radial lamellae that contain dentinal tubules (Heckel, 2009; 2018).

Ivory is an effective raw material for artefacts, as it has high resistance to fractures and thus conducive to efficient energy transfer (Saunders, 1979; Espinoza and Mann, 1993; Sui and Cui, 1999; Locke, 2008; Heckel, 2018a; Pfeifer *et al*., 2019). The resilience and durability of ivory surpass that of other osseous materials, which were also used by Palaeolithic people (Pfeifer *et al*., 2019; Girya and Khlopachev, 2018). Khlopachev and Girya (2010) demonstrated how to process and knap frozen mammoth ivory without cracks recovered from the Siberian Permafrost and in a very good state of preservation. They knapped the frozen ivory in a similar way to lithics and produced flakes of more than 20 cm in length. This approach also demonstrates the suitability of mammoth ivory as a raw material for the manufacture of tools.

Another advantage of this material is that tusk pieces can be larger than bone or antler, allowing Palaeolithic people to produce larger tools that were less constrained by the natural size of the osseous materials.

Archaeological context

Woolly mammoths (*Mammuthus primigenius*) lived in Central Europe, including the Swabian Jura during the Late Pleistocene (Lister and Bahn, 1997; von Koenigswald, 2002; Niven, 2006; Münzel, 2001, 2019). No other Proboscidean species has been identified within the Upper Palaeolithic layers of the Swabian Jura, and we assume that all ivory remains derive from the tusks of woolly mammoth.

Material from the Swabian Aurignacian has yielded calibrated radiocarbon dates between 43,000 and 35,000 years B.P. (Conard and Bolus, 2003, 2008; Conard, 2009; Higham *et al*., 2012; Bataille and Conard, 2018). The exploitation of mammoth ivory during the Swabian Aurignacian is well documented, for example, Riek (1934) excavated Vogelherd Cave near Niederstotzingen in the Lone Valley and published on the rich ivory artefacts from the site.

Hahn (1988, 1992) has also documented the same for Geißenklösterle near Blaubeuren and demonstrated that the whole manufacturing process of artefacts including personal ornaments took place on site. Conard *et al*. (2003, 2006) noted that the density of processed ivory in Geißenklösterle is higher in the older Aurignacian layer III than in the younger Aurignacian layer II, showing variability of ivory processing within the Aurignacian. Over the long history of research in the region, excavators have recovered vast assemblages of ivory artefacts including dozens of figurative artworks, multiple flutes, numerous and diverse personal ornaments and various tools, such as points (Riek, 1934; Hahn, 1986, 1988; Conard *et al*., 2004, 2009; Conard, 2009; Wehrberger, 2013; Wolf, 2015; Wolf and Conard, 2015; Dutkiewicz *et al*., 2018; Dutkiewicz, 2021; Conard and Rots, 2024). In addition, other artefacts such as polished ivory pieces, debris and flakes, which appear to be by-products of ivory processing, have drawn the attention of archaeologists (Wolf, 2015; Heckel and Wolf, 2014). Until now, there was no clear evidence that these by-products were used as tools or whether they were simply debitage from ivory processing.

Hohle Fels Cave

One of the sites with the highest density of archaeological material in the region is Hohle Fels Cave. Fraas and Hartmann conducted the first excavations in Hohle Fels Cave 1870/71 (Fraas, 1872). About 100 years later, Joachim Hahn started excavations in 1977. In 1997 Nicholas Conard took over and continues to excavate the site in yearly campaigns (Conard and Wolf, 2020). The main excavation area from the late 1970s concentrated on the corridor that connects the entrance to the main chamber. The history of occupation ranges from Middle Palaeolithic to the present (Conard and Janas, 2021). During the Palaeolithic, cave bears used the hall as an ideal niche for hibernation while human occupation was more intensive in the corridor area and more orientated to the entrance.

Here, the Palaeolithic groups had daylight. Most materials excavated from the area were recovered using modern sieving standards, ensuring the recovery of smaller artefacts and materials with a size smaller than 1 cm. The last quarter century of excavations has revealed a rich and varied record of ivory artefacts within a well-stratified context (e.g. Conard and Uerpmann, 1999; Conard and Malina, 2011, 2012, 2016; Taller, 2014; Taller and Conard, 2016). Conard's team has identified a minimum of five Aurignacian archaeological horizons (AH IIe - Vb) as well as features within the layers that contain a high density of anthropogenic material and numerous artefacts (e.g. Conard and Malina, 2004, 2012, 2016). Important finds originate from each of the archaeological horizons IIe-Vb. This whole Aurignacian sequence dates radiocarbon to ca. 42,000 - 35,000 years cal. BP (Conard, 2009; Bataille and Conard, 2018; Kitagawa and Conard, 2020). Spatial analysis demonstrates that ivory knapping took place in every Aurignacian horizon (Wolf, 2015; Heckel and Wolf, 2014). During the Swabian Aurignacian in Hohle Fels the production of personal ornaments is well known.

Geißenklösterle

Geißenklösterle Cave is located a short distance from Hohle Fels near Blaubeuren. It is a partially collapsed cave located on a slope, about 60 meters above the current level of the river Ach (Hahn, 1988). The site was discovered in 1958 and excavated in multiple campaigns by Eberhard Wagner in 1973, by Joachim Hahn between 1974 and 1991, and by Nicholas Conard in 2001 and 2002. The Upper Palaeolithic layers consist of the Lower Aurignacian (AH III) dated to ca. 43,000-42,000 years cal. BP, the Upper Aurignacian (AH II) dated to ca. 42,000-38,000 years cal. BP, the Gravettian (AH I) dated to ca. 35,000-30,000 years cal. BP, and a very small Magdalenian component (AH Io) (Richter *et al.*, 2000; Higham *et al.*, 2012). Geißenklösterle contains abundant evidence of Aurignacian symbolic material culture including ivory figurines, bone and ivory flutes, personal ornamentation, and one painted stone (Hahn, 1988; Floss, 2015; Wolf, 2015; Dutkiewicz, 2021).

Chisels

Conard and Malina interpreted three ivory artefacts from Hohle Fels with battered ends as chisels (Conard and Malina, 2020) (See Figure 2).

These artefacts were recovered in close proximity to one another from Aurignacian layer IV (Wolf, 2015; Conard and Malina, 2020) (See Figure 3a and 3b; Figure 4).

The 14C dates of this layer provide dates of around 39,000 years cal. BP (Conard and Bolus, 2003, 2006; Higham *et al.*, 2012; Bataille and Conard, 2018). The three artefacts are on permanent display in the Urgeschichtliches Museum Blaubeuren. A chisel is defined here as a tool to work hard materials in a reductive process that allows the makers to control the driving forces of percussion. It can also serve as an intermediary tool which can be used together with hammers to initiate indirect percussion with an ultimate aim to divide and split. In the latter case the tool is used similar to a punch in flint working, when a rod that is made from an osseous material directs the force applied to the top of the punch to the desired point of a flint core in a controlled way in order to produce a flake (Hahn, 1991; Floss, 2012).

Oftentimes one end of the chisel is wedge-shaped to maximize the transfer of energy for a particular target and to penetrate through the material (website: www.duden.de). Chisels possess similar modifications that are described by Tartar (2009, p. 150) concerning *pièces intermédiaires*. Unlike these intermediary tools, the chisels from Hohle Fels are shaped and fashioned more thoroughly from the distal to the proximal end with the aim to reproduce a specific design.

The chisels differ from bevelled artefacts, which are used as a tool for splitting and which are similar to the *pièces intermédiaires*. Those tools could possibly be inserted in narrow crevices.

In contrast to chisels, the bevelled artefacts sometimes lack the shaping phase (finition) and may appear in diverse shapes. They are not standardized: these objects can be carved from debris and flakes that were results of the reduction process of a tusk (Khlopachev and Girya, 2010; Wolf, 2015). The concave side has often been reduced in volume, resulting in a bevelled surface.

The production of a chisel requires planning. Groove and splinter technique, which is common in the Gravettian, is not directly documented in the Swabian Aurignacian (Wolf, 2015).

However, hints of this technique exist, such as a groove on a piece of cementum from the Vogelherd Cave near Niederstotzingen, from the Aurignacian horizon IV (See Figure 5; Riek, 1934) as well as the manufacture process of the Aurignacian ivory flute of Geißenklösterle Cave that includes splitting a rod in half (Conard *et al.*, 2004; Malina and Ehmann, 2009; Hein 2018, 2021). Thus, for the preparation of the manufacture of a chisel, the Aurignacian people very likely split tusks and extracted the rod by using one edge of a split half as a longitudinal edge for the desired rod. Another method would be to carve a deep circumferential groove and break the tusk at this groove with force afterwards. The Aurignacian people may have directly knapped these tusk parts in order to extract debitage as raw forms to work them into a shape (Semenov, 1957).

Those objects were smoothed and polished along the longitudinal axis and the ends were completely shaped before use. It is noticeable that the tusk's periphery, the layer of cementum with a bigger part of larger dentine was used to create the chisels presented here (See Figure 6).

Inv.-n°: 100/2254

The piece was initially found as three larger pieces in proximity to one another within feature IV. This object measures 217.5 x 35.8 x 24.7 mm and is almost complete with little loss of the matrix besides the proximal end. The end appears heavily battered. The convex part consists of cementum and the concave part is dentine. It is one of the largest ivory tools besides the projectile point, which has been recovered from the same layer (Wolf, 2015). It has a largely cylindrical form with a circular cross-section for the proximal half and roughly semi-circular for the distal half. The head shows a slight knob-like protrusion that allows for a larger hitting surface and greater transfer of force. The battered surface shows deformation of the structure of the dentine. A series of notch marks on the lateral sides helped reduce the overall thickness of the distal half and shape it into a wedge form.

Inv.-n°: 100/2345

Measuring 167.8 x 31.1 x 14 mm, the piece is broken on one longitudinal side. Nevertheless, the object is preserved at its proximal part and there retains an oval cross section. The dentine makes up most of the artefact, but there is a layer of cementum on one of the larger faces. On the dentine side, there is heavy black staining. Despite the discoloration, longitudinal- transversal scraping marks on the dentine are an indication of shaping. The proximal end shows battered damage (See Figure 7). From the profile, the bent feature of the dentine microstructure is visible. The damage runs from the mesial to distal end. The surface is a fresh and longitudinal fracture plane. Also, there are smaller pieces of the matrix missing from both sides of the proximal end. The distal end is round in its cross-section and shows slight battered damage.

Inv.-n°: 100/2368, refitted to 100/2555

This piece measuring 135.8 x 29.9 x 12.8 mm is less complete than the previous two, with a missing proximal and medial end at the body of the artefact. The plane of the fracture follows the natural structure of the ivory and likely resulted from the loss of collagen and the splitting of ivory along the microlaminae in the ivory. This transversal break possibly resulted from taphonomic processes as this is an indication of the alteration of the ivory (see above).

Weathering is partially visible on one of the faces that obscured any technological or functional traces. On the other plane, the negative scars of the missing fragments that made up the entirety of the specimen are visible. The distal end is round in its cross-section and partially shows rounding and battered damages.

Other Ivory artefacts with battered ends are also documented at Geißenklösterle, in AH III (Hahn, 1988; Wolf, 2015). This includes a complete bevelled artefact (GK IIIa, 67/1860) as well as flakes and debris (See Figure 8 and 9).

Material and Methods

The present authors aimed to determine if the artefacts described here, could be used as chisels. A secondary aim was to determine which possible action could have caused the ends with battered damage, as the damage does not show the natural breakage pattern or delamination described above. With the help of experimental work, we tested different scenarios of use and drew conclusions concerning the behaviour of the Aurignacian users of these tools.

Working hypothesis 1: These mammoth ivory tools were used to work osseous materials like mammoth ivory.

Working hypothesis 2: The tools were used for a long duration to get the typical unravelled edges we observe on the artefacts. We assume several hours of intensive use until these patterns occur.

To conduct the experiments, we first set out to obtain the raw material, ivory, to conduct our experimental work. Today, we have access to mammoth ivory that comes from the Siberian permafrost, which is legal and can be purchased, but the material is mostly saturated with moisture. It is also modified by taphonomic processes such as the partial diagenesis and accumulation of various minerals in the matrix of the ivory (Banerjee and Bortolaso, 2004). For the purpose of this experiment, we needed ivory that corresponds to the conditions of ivory that the Aurignacian people had at their disposal. With a very high probability they could access fresh, massive pieces of tusks from mammoths that either lived contemporaneously or remained 'fresh' in colder conditions. This is partially documented by ivory 'knapping' from multiple debris. The production of massive ivory tools with a length that extends 20 cm indicates the extraction of long objects from flawless ivory to manufacture these chisels (oral communication Gennady Khlopachev, Sankt Petersburg March 2012). Therefore, the tusks of African elephant were the best material for the purpose, because the structure resembles mammoth ivory very well (Locke, 2008). The Bundesamt für Naturschutz in Bonn (BFN) (D) (https://www.bfn.de/; visited the 1st of June 2022) coordinates the administration of ivory of the African elephant that is known and stored in Germany. Although elephants are protected by CITES (https://www.bfn.de/thema/cites; visited the 1st of June 2022) the BFN allocates ivory for scientific research after the assessment of requests. To this end, the information of the disposition of the ivory which is used for scientific purposes is fully documented and retraceable for the agency.

We requested a tusk piece of an African elephant with a diameter of 8 cm and minimum of 30 cm in length. These dimensions were needed to carve objects that resemble the Aurignacian artefacts already described in detail. The BFN approved and provided a part of the tusk with this dimension for our experimental study (See Figure 10a).

Our aim was to build up a reference collection for the Department for Prehistory and Quaternary Ecology at the University of Tübingen with these objects. For the reasons mentioned, it is not possible to work experimentally with large ivory objects. We see our work as an attempt to gain a better understanding of how ivory was worked in the Palaeolithic period.

The working plan was the following:

1. Microscopical investigation of the artefacts HF 100/2345, HF 100/2254, HF 100/2555
2. 3D scans of the original artefacts HF 100/2345, 100/2254, 100/2555 to store them in a digital way for the scientific community

3. 3D prints of the digital files in order to have templates for carving objects for experimental use
4. Carving of objects from African elephant ivory that resemble the three Aurignacian items HF 100/2345, HF 100/2254, HF 100/2555
5. Conduct the experimental work with proper documentation in place
6. Comparison of the original finds and the experimental pieces, also with the use of the 3D digital microscope Hirox HRX-01 with a magnification range of 20 x to 2500 x

The artefacts were scanned with an Artec Space Spider, and 3D prints were made with the printer Formlabs Form2, with V4 resin with a width of 50 µm in the Department for Early Prehistory and Quaternary Ecology at the University Tübingen. Bernhard Röck, a professional ivory carver in Erbach/Günterfürst in the Odenwald created the replicas. This required electric devices, including a Bandsäge Elektra Beckum BAS 500 Metabo Germany, a 3 mm wide saw blade and a grinding machine and electric Handpiece (Dremel) with attachment with hardened shaft to create objects similar to the three initial pieces (See Figure 10c). Röck sawed the tusk fragment in half (See Figure 10b). He used one half to create the objects for the experimental work. The 3D prints of the artefacts served as templates and orientation for Röck to shape the objects of African elephant ivory in similar sizes and forms as the originals (See Figure 10d). Röck created three chisel-shaped objects that are similar in size to the original artefacts from Hohle Fels, but without any fracture or breaks, which are visible on the original artefacts. Due to the small amount of raw material available, we decided to not produce more objects for this first experimental approach. The second half of the tusk part was needed as a working base for actions 3 and 4, which require a crack-free, stable piece of ivory (see below). Rudolf Walter prepared a longitudinal groove on the cementum on the second half of the tusk to prepare the piece for the experiments using a flint burin. Walter stored object n° 3 in a freezer at -23C° for four weeks to assess whether this facilitates ivory working as proven by Khlopachev and Girya (2010, 2018).

Experiments

The experimental work took place in the Eiszeit- Forschungs- und Vermittlungsstudio Hohle Fels Schelklingen (Eiszeitstudio Schelklingen).

The actions we undertook concerned the respective distal and proximal ends of each object. We experimented with four possible scenarios and actions. The actions should be simple but effective to test the use of the "chisel": grinding, pounding, striking, and hammering. The activities were intended to imitate possible work with chisel-like artefacts in the Palaeolithic. Grinding and pounding emulates plant processing, using the rounded end (on Figure 3 described as proximal end). Plants were most likely also ground or pounded to prepare them for consumption (e.g. Weiss *et al.*, 2008; Revedin *et al.*, 2010).

Striking and hammering are the actions we hypothesized for a splitting process. We started with the action that would probably have the least impact on the surfaces:

Action 1. Grinding: Pestle on a flat plate made of Jurassic limestone (See Figure 10e)

We ground the local common sorrel [Rumex acetosa] (which was present in the Palaeolithic [Bigga, 2018]) on a Jurassic limestone plate with half rotating, regular movements of the right hand by using the replica made from African elephant ivory as a pestle in order to attempt to break up the fibres of the sorrel. The pressure we measured with the scales was 12 kg weight. The active area on the replica was what we would identify as the proximal end of the artefact 100/2254.

Action 2. Pounding on the flat plate

We pounded the common sorrel on a Jurassic limestone plate for the entire duration.

Action 3. Striking/Hitting on the proximal surface (See Figure 10f)

We hit the proximal end of the tool with a greywacke from the Danube weighing 750g to deepen a longitudinal groove within the second half of the elephant tusk that was not used to prepare objects for this experimental work. During the hitting, we moved the object bidirectionally for a distance of two cm within the groove. After 1 minute and thirty seconds we turned the piece so that both sides of the distal end were used.

Action 4. Hammering on one point

For this action, the greywacke was used to hammer steadily on the proximal end on one point.

Each action lasted 3 minutes. We carried out the actions consecutively. We chose the time span for all the work steps because it is very strenuous even for an experienced experimental archaeologist to carry out the work in succession. Only a short break for the photo documentation of approximately five minutes lay between the different working actions. The hypotheses were that these actions should leave traces on the objects that we could document and compare with the original artefacts in order to retrace actions Palaeolithic people did. This warranted a good comparability of a) the surfaces and b) this gave the opportunity to retrace our work for others.

We used the objects made by Röck with the numbers No.1, No.2 and No.3 which closely resemble the archaeological pieces in size and shape. Object n° 1 resembles the archaeological find inv.-n°: 100/2254 without the lateral removal of ivory pieces due to technical and temporal constraints. In addition, object n° 2 resembled that of the artefact inv.-n°: 100/2345 and object n° 3 resembled that of artefact inv.-n°: 100/2368. The focus lay on the proximal and distal ends of the experimental pieces with an aim to reconstruct the battered damage, including micro-splintering and bent fibres. Due to the limited raw material and available objects with appropriate size, the replicated artefacts were reused after documentation by removing the matrixes from the proximal end through sanding down the surface using sandpaper with 400 grit size. We documented the respective traces after the action using a camera with macro lens. As this was a first approximation of the possible work of Palaeolithic people, we considered this to be sufficient for our approach. The lateral edges of the objects are not of interest for the observations because no action took place on these edges.

Results

Object 1 (See Figure 11)

Action 1: The active surface of this object, interpreted as the proximal end of the archaeological object, changed little except for a light polish on the surface and light green discoloration from the plant.

Action 2: The active surface of this object, interpreted as the proximal end of the archaeological object, shows small micro-depressions (See Figure 12,3).

Action 3: The proximal surface (hammer head) changed from its original white colour to yellow in the area with heaviest contact with the force of the hammerstone, likely resulting from collagen enrichment (See Figure 12,4). Few splinters resulted from the distal end when it was hit against the ivory half-block with a groove, which did not show any modifications. The friction of the ivory on ivory resulted in collagenous odour and some heat.

Action 4: Small depressions emerged on the proximal surface, and the discolouring increased (See Figure 12,5). The distal end shows a small battered part on the convex, distal part and slight discoloration similar to the proximal end (See Figure 11, a).

Object 2 (See Figure 13)

Action 1: The proximal surface of the object did not change except for a slight green discoloration from the plant matter.

Action 2: The proximal surface shows small depressions resulting from the contact with the limestone plate.

Action 3: The hitting surface on the proximal end changed its colour from white to yellow in a concentrated area. Furthermore, two small longitudinal cracks arose at the weakest point of the tusk fragment along the growing lines. The piece splintered (See Figure 13, 4 a, b). After 1 minute and 30 seconds we turned the piece so that both sides of the distal end were under the same amount of stress.

Action 4: The distal end showed a 'crushed' edge with a highly damaged surface (See Figure 13, c) and an elongated chip became detached on the lateral edge. The damage exposed microstructures of the ivory and bending of the edge. The ends became frayed and the piece splintered. Also, on the proximal part a flake was chipped on the concave part close to the edge of the battered end.

Object 3 (frozen) See Figure 14)

Action 1: The proximal surface of the object did not change except for a slight green discoloration from the plant.

Action 2: The surface of the object showed no modifications.

Action 3: On the proximal convex part, a crack appeared and the surface showed battered damage that resembles compression. The distal end also shows similar damage with battered, micro-splintering (See Figure 14, 4c). Small splinters resulted from the action in a radius of 50 cm.

Action 4: The edges of the proximal end became bent. A flake was removed where the crack emerged during the third working action close to the proximal end (See Figure 14, 2b). After one minute, a splinter came off along the left side of the piece (See Figure 14, 3; splinter: Figure 14, 7- 10).

General Summary

In our experimental approaches, we recreated possible ways of working with chisel-shaped objects that are similar to Palaeolithic actions. At this stage, we cannot imagine other procedures to create the traces like the battered ends, although we of course do not exclude them. For example, researchers like Khlopachev and Girya (2010), who did experimental work on mammoth tusks and presented archaeological remains made from mammoth ivory, did not report the same traces observed on the ends of the Hohle Fels and Geißenklösterle artefacts. With our first approach we are at the beginning of an understanding of Aurignacian daily work with mammoth ivory. In any case, our experiments delivered adequate results to test our hypotheses. In summary, the working actions to pestle and pound plant materials mostly produced little alteration except for small depressions due to the contact with the limestone.

The result of these two actions was that a surface change occurred. We are aware that the first two actions could cause micro-fractures in the ivory and facilitate the splintering of the ivory, but for the first two actions, splintering was not the case due to the high strength of the material, elephant ivory. We therefore assume that the first two experiments had no serious effects on the two subsequent actions.

The actions of hitting and hammering created more wear on the objects, resulting in similar observations on the proximal and some distal ends with battered surfaces. The characteristic traces occur after a short time, even after 2-3 minutes of their use as chisels (See Figure 15). The impact force caused the battered edges and very probably the flakes. With controlled beating pace and force, it is reasonable to assume that the bent structures become more intense with prolonged use. Freezing ivory changes the material properties and the ivory shatters more easily. Overall, the experimental pieces resemble the archaeological pieces of Hohle Fels and Geißenklösterle which show the characteristic bent surfaces at one or two ends, which supports their functional attribution as chisels to work osseous materials.

Working ivory with ivory chisels left similar traces on the experimental pieces as on the original archaeological artefacts. This underlines our hypothesis 1: These mammoth ivory tools were used to work osseous materials such as ivory. The use of ivory chisels on ivory resulted, however, in heavy modifications of the ends in a matter of 2-3 minutes, disproving hypothesis 2, that the tools were used for a long duration to get the typical unravelled edges we observe on the archaeological pieces. In any case, further work with other materials like antler is pending in order to substantiate or question the thesis put forward here.

Discussion

Through this study, we demonstrate that using ivory tools to work ivory represents a viable hypothesis for the use of these chisels. The bent structure is a sign of heavy force deforming the ends of the tools through force and that this pattern is not a result of other taphonomic factors or natural fracture. Ivory serves as an outstanding medium for chisels in this context, because it is dense and can withstand heavy impacts (Pfeifer *et al.*, 2019). Nevertheless, this study does not exclude the use of other hard raw materials such as lithics to split osseous materials, which was not employed in this experimental approach.

The Aurignacian inhabitants of the Swabian caves likely used ivory chisels to reduce larger tusk fragments and to produce smaller ivory pieces as objects for a multitude of artefacts. In addition to the chisels from Hohle Fels and Geißenklösterle, other smaller ivory pieces show similar battered edges on one or both ends (See Figure 8 and 9). Given that percussive actions create these battered edges, these bevelled artefacts likely served as wedges for working hard materials including ivory. We note the absence of standardized morphologies among these bevelled artefacts although ivory flakes were chosen frequently. Heckel and Wolf (2014) have demonstrated that raw forms for such non-standardized bevelled artefacts can be produced by direct hard hammer knapping of mammoth ivory, which is particularly effective at sub- freezing temperatures of ~ Minus 18 C° (after Khlopachev and Girya, 2010) (e.g. Figure 9 and 4, HF 100/3270).

The use of osseous materials to work other osseous materials, including antler on antler (Baumann and Maury, 2013), has been discussed in other Aurignacian contexts, and seems to be a practical design solution, reflected in diverse artefact types made from antler, bones and ivory. The use of wedge-like implements made of bone and antler for splitting mammoth ivory is recorded in Yana site in Siberia (Pitulko *et al.*, 2004). This technological pattern appears with the spread of modern humans into Europe approximately 43,000 years ago (Conard and Bolus, 2015). In areas where cervids and woolly mammoths were abundant, Aurignacian hunter-gatherers began to use osseous materials within diverse toolkits. Liolios (1999) and later Tartar (2009, 2015) note for the Aurignacian sites in southwestern France a selection of different osseous raw materials for special artefacts dedicated to a specific purpose. In this region, antler was mainly used to manufacture hunting weapons, bones for the fabrication of domestic equipment, and ivory to carve personal ornaments of different kinds.

This selection is explained, among other things, by the low occurrence of ivory in this region and not with a cultural choice (White, 1995; Heckel, 2018b). Over the course of the Upper Palaeolithic, *Homo sapiens* continued to use ivory wherever it was available. This is very well expounded for Northern Siberia where hunter-gatherers extensively exploited mammoth tusks and used ivory tools about 45,000 years ago (Pitulko *et al.*, 2016) until mammoths were not available anymore and a decline of ivory took place (Pitulko *et al.*, 2004, 2015, 2016). Only then, a raw material change is observed, a shift from ivory to micro blade technology (Pitulko *et al.*, 2004).

During the European Early Upper Palaeolithic innovations including figurative art and personal ornaments made from mammoth ivory demonstrate the craftsmanship of these hunter-gatherers (Otte, 1979; Sinitsyn, 2003; Floss and Rouquerol, 2007; White *et al.*, 2015; Wolf and Heckel, 2018; Straus *et al.*, 2022). The Swabian Aurignacian represents a unique assemblage of diverse artefacts made from mammoth ivory including rope-making tools, figurative art, musical instruments, and personal ornaments (Riek, 1934; Hahn, 1986, 1988; Conard *et al.*, 2004, 2009; Floss and Rouquerol, 2007; Conard, 2009; Wehrberger, 2013; Wolf, 2015; Wolf and Conard, 2015; Dutkiewicz *et al.*, 2018; Wolf and Heckel, 2018; Dutkiewicz, 2021; Conard and Rots, 2024). The best-preserved flute made from ivory derives from Geißenklösterle Cave (Hahn, 1988). Its method of manufacture has been reconstructed several times (Malina and Ehmann, 2009; Hein, 2018, 2021). Since, for now, open-air

Aurignacian sites with organic preservation are unknown in Swabia, our attempts to contextualize the social-economic role of ivory artefacts relies exclusively on information from the many well-known caves of the region (Conard and Bolus, 2003, 2008). We can demonstrate that primarily symbolic artefacts such as figurines, musical instruments and personal ornaments are often found at rich residential sites, where people spent long periods of time (Riek, 1934; Conard and Wolf, 2020). Thousands of mammoth ivory shavings and splinters attest to intense ivory processing on site in Hohle Fels as well as in Geißenklösterle (Liolios, 1999; Conard *et al.*, 2003, 2006; Wolf, 2015). In this framework, we characterize the chisels as tools employed within the parts of these caves, where Aurignacian people lived and worked. We hypothesize that ivory chisels and bevelled artefacts often belonged to tool kits at residential sites. The Aurignacian people invested significant time and resources into the production of completely reworked chisels. Within a short time of use of these chisels, they worked off the edges with a great deal of effort. The question arises, why? Perhaps the end product was not as important as the action performed? Many questions still remain unanswered. We assume that such a tool could have been in use for multiple work steps, even after the proximal end was worn down. The exploitation of ivory in this region is unprecedented, and the raw material ivory played a particular role in the development of early Aurignacian material culture. The manufacture and use of chisels are crucial building blocks within this material culture to fulfil all production steps required to carve specific objects. Ivory chisels and bevelled artefacts represent essential tools for obtaining the initial forms for artefacts including diverse tools used for hunting purposes, figurative art, musical instruments, and personal ornaments. Chisels played a central role in splitting and shaping suitable preforms for all of these classes of artefacts. The clearest evidence for this ivory splitting and shaping technology comes from the Ach Valley cave Hohle Fels and Geißenklösterle. The great abundance of mammoths and ivory in the landscape of the Swabian Jura is consistent with the richness of the Aurignacian ivory industry. The archaeological abundance of unused ivory suggests that the ivory workers did not need to conserve this important raw material (Riek, 1934; Hahn, 1988; Wolf, 2015; Wolf and Conard, 2015). As a conclusion, in many respects, based on the wealth of ivory artefacts as tools and within symbolic spheres, one could view this period in the Swabian Jura as the Age of Ivory. Working ivory and making artefacts from ivory testifies to complex cognitive and manual skills. Concerning ivory working this also means the Palaeolithic craftspeople imagined their desired object at an early stage of breaking down a tusk and considered the form to be created in advance. Unlike other materials, where the raw material itself dictates or creates major limitations on the size and form of manufactured artefacts, mammoth ivory typically has a high volume and often a length of over a meter (Kahlke, 2005). These large dimensions and the uniform quality of ivory creates enormous opportunities for innovative designs of diverse tools and symbolic artefacts. The extensive exploitation of tusks and the carving of ivory in Eurasia is mainly associated with the early Upper Palaeolithic. To our current knowledge, this technology has no direct precursors so far, although ivory was used, and the ivory processing developed quickly at the start of the Aurignacian. These hunter-gatherers developed a profound knowledge of the useful properties of ivory, which established itself and continued in southwestern Germany for a minimum of 6,000 years. The archaeological record from broadly contemporaneous caves in Belgium documents a similar pattern (Otte, 1979; Straus *et al.*, 2022). Mammoth ivory was also worked into specific tools such as hammers at the Austrian Aurignacian site of Alberndorf I (Steguweit, 2005). With the start of the Gravettian in Swabia roughly 35,000 years ago, the abundance and diversity of ivory artefacts declined sharply and was limited primarily to new forms of personal ornaments, most notably teardrop- shaped pendants (Zotz, 1955; Riek, 1973; Scheer, 1985; Vercoutère and Wolf, 2018). After the Swabian Aurignacian, ivory tools nearly disappeared from the archaeological record of Western and Central Europe, while becoming exceptionally abundant and diverse during the Pavlovian, the Eastern European Gravettian and the East European Epigravettian (Bosinski, 1987; Abramova, 1995; Gvozdover, 1995). Remarkable are the Gravettian boomerang from Oblazowa Cave in southern Poland (Valde-Nowak *et al.*, 1987) or so-called "spoons" and "pièces esquillés" of the Pavlovian (Klíma, 1983; Valoch, 2013; Oliva, 2015, 112). Ivory chisels remain in the archaeological inventories, like in the Russian sites Yana (Pitulko *et al.*, 2004) or Kostenky 1 (Efimenko, 1958; Khlopachev, 2016, 262-264). Remarkable are also the "outils cylindriques" of the eastern Epigravettian of Mezyn (Vercoutère, 2018).

Over time, ivory tools remained an integral part of the Palaeolithic site assemblages where the material was abundant and accessible. Ivory carving was certainly already a driver for the cultural development of *Homo sapiens* at the beginning of the Upper Palaeolithic. The Aurignacian hunter-gatherers of the Swabian Jura knew the unique qualities of the material, valued these properties, and systematically implemented these characteristics in their designs and technological decisions. Although in exceptional cases, ivory working occurs prior to the Aurignacian, during the Swabian Aurignacian, the use of ivory was embedded in everyday life. Large amounts of ivory debris, bevelled artefacts and crafted chisels with their battered ends document the intense exploitation and reliance on this durable and aesthetically attractive raw material. Ivory workers produced a vast diversity and abundance of unique artefacts, many of which serve as reliable chrono-cultural markers for the Aurignacian in this region. The extensive use of ivory became possible in connection with the development of ivory splitting, knapping and shaping methods. The ivory chisels and bevelled artefacts represent essential aspects of this early Upper Palaeolithic technology and count among the unique inventions of the Swabian Aurignacians. The material culture of the Swabian Aurignacian, including specialized ivory working, illuminates the innovative capacities of early Upper Palaeolithic people.

Acknowledgement

We deeply thank Herr Rudolf Thelen (Bundesamt für Naturschutz Bonn) for providing us with a tusk piece for our scientific experiments. We thank Madison McCartin for doing the 3D scans as well as Alexander Janas from the Senckenberg Centre HEP for printing these scans as 3D items. We are grateful to Bernhard Röck for the production of the experimental templates in his workshop. As always, he generously shared his vast knowledge, years of experience and time with us.

Funding: This work was not funded by external means or external institutions. Authors Contribution

Conceptualization, S.W., and K.K.; Methodology, S.W., K.K. and R.W..; Investigation, S.W. and R.W.; Writing-original draft preparation, S.W., K.K. and N.J.C.; Review and editing, S.W., K.K., R.W. and N.J.C.; Visualization, A.F. and S.W.; Project administration, S.W.; Resources, S.W., R.W. and N.J.C. All authors have read and agreed to the published version of the manuscript.

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Keywords ivory

Country Germany

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Gallery Image

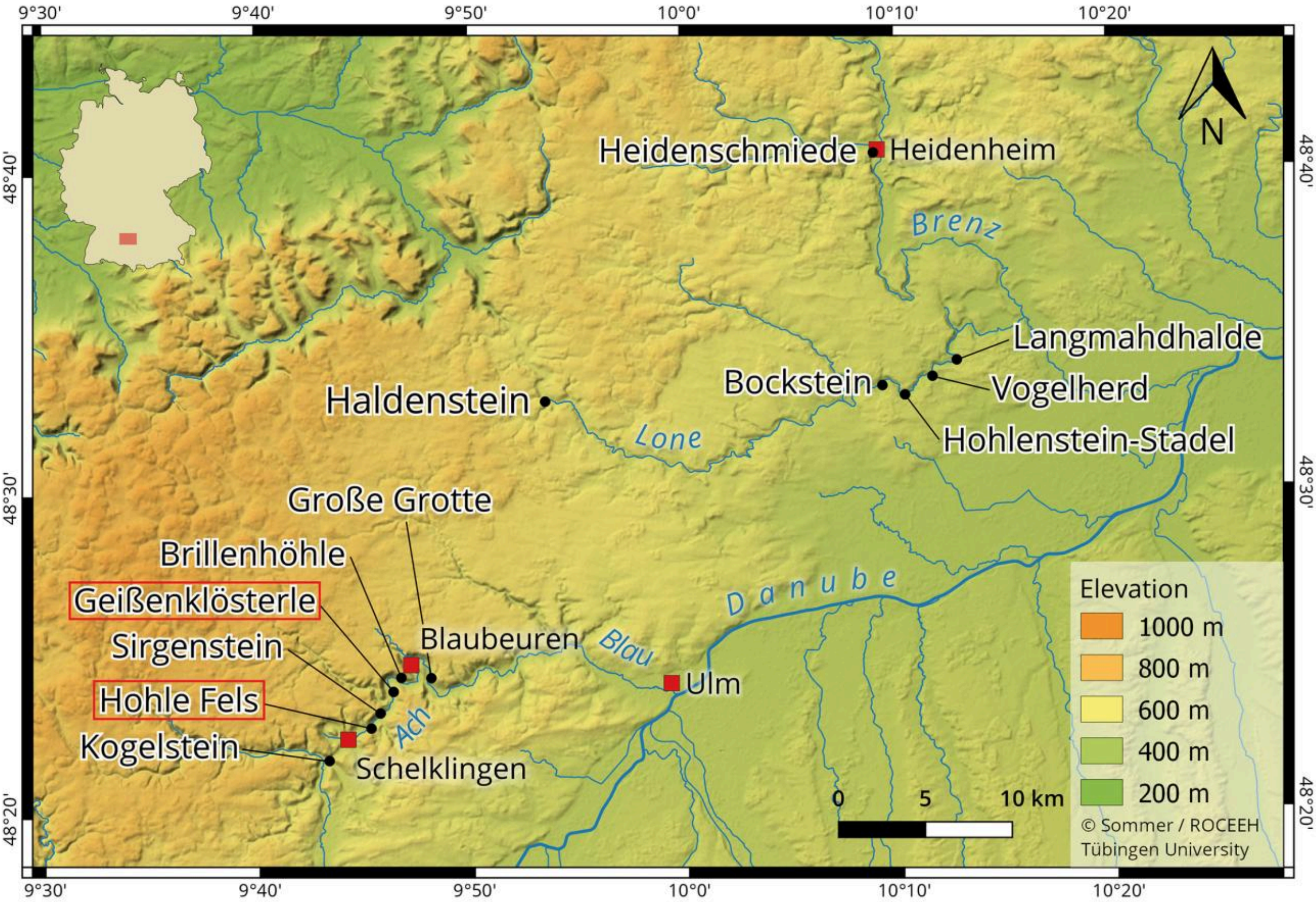

FIG 1. SITES WITH PREHISTORIC REMAINS IN THE SWABIAN JURA, SOUTHWESTERN GERMANY. RED FRAME: HOHLE FELS CAVE AND GEISSENKLÖSTERLE CAVE, LOCATED IN THE ACH VALLEY. IN THESE SITES, BEVELLED IVORY ARTEFACTS WERE EXCAVATED. MAP: C. SOMMER, ROCEEH; MAP BASE: SITE COORDINATES AFTER M. MALINA, G. TONIATO, AND THE ROAD DATABASE; ELEVATION FROM SRTM V3; HYDROLOGICAL NETWORK FROM LUBW; COUNTRY BOUNDARIES IN THE INLET ARE FROM NATURAL EARTH; THE FONT IS OPEN SANS; DOI:10.5281/ZENODO.3460300, CC-BY 4.0 LICENCE.

FIG 2. HOHLE FELS, CHISELS, FRONT VIEW, REAR VIEW, LATERAL VIEWS, TOP VIEWS, ARCHAEOLOGICAL HORIZON IV. THE DETERMINATION OF THE PROXIMAL AND DISTAL ENDS TOOK PLACE AFTER OUR EXPERIMENTAL WORKS. IN THE MAGNIFICATION OF OBJECT 100/2254 THE NOTCHES ON THE LATERAL EDGES CAN BE OBSERVED THAT THE AURIGNACIAN CARVER MADE IN ORDER TO CHIP OFF A PART OF THE OBJECT IN ORDER TO GET A BEVELLED END. PHOTOS BY A. FATZ, SHEP TÜBINGEN..

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FIG 3A. HOHLE FELS NEAR SCHELKLINGEN. PHOTO BY JENS BURKERT.

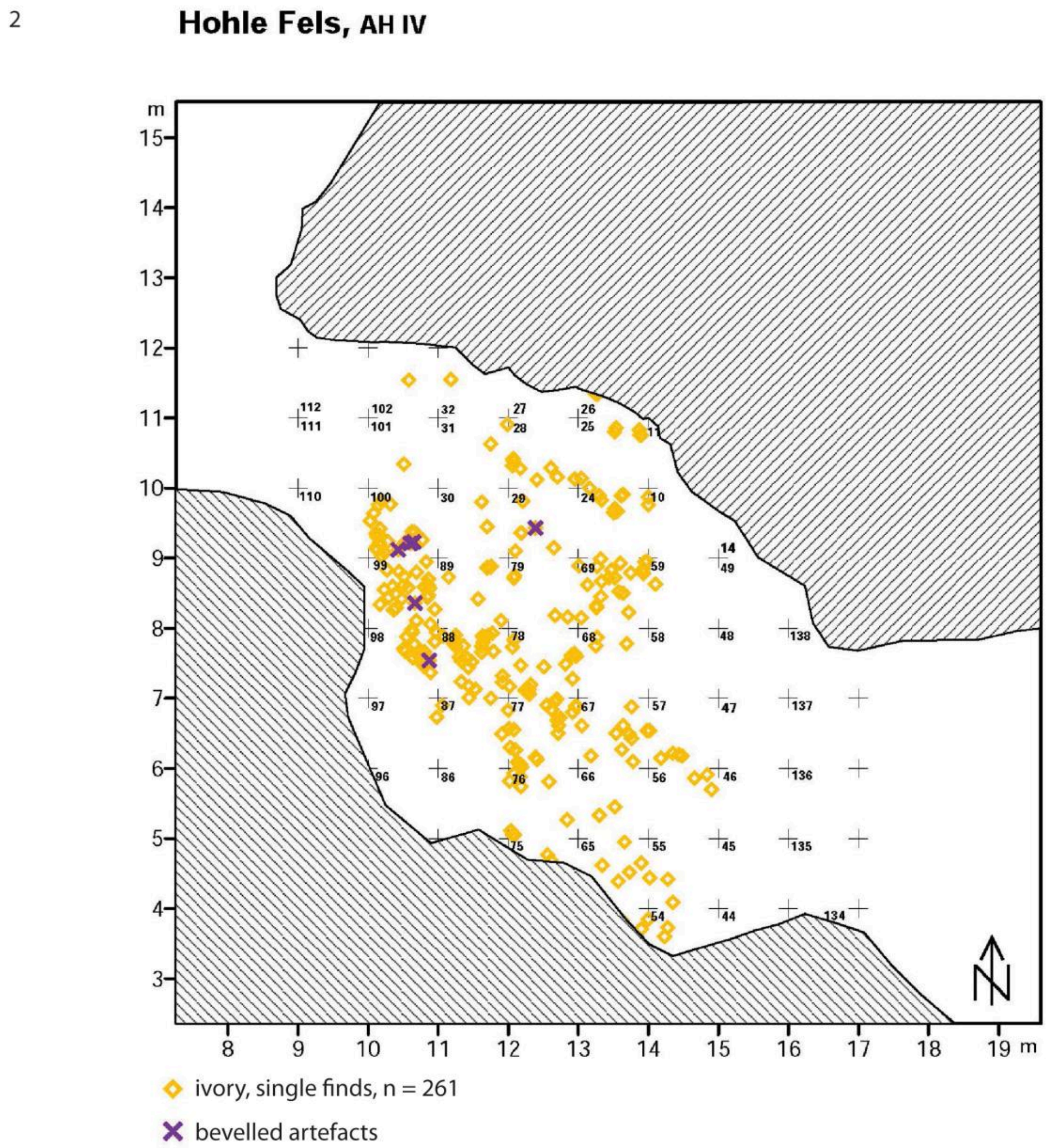

FIG 3B. HOHLE FELS, ARCHAEOLOGICAL HORIZON IV. PLOT (SURFACE TOP VIEW, SOFTWARE SURFER) OF SINGLE FINDS MADE FROM MAMMOTH IVORY (> 1CM, IN YELLOW) AND BEVELLED ARTEFACTS MENTIONED IN THE ARTICLE (IN PURPLE). PLOT BY A. JANAS, SHEP TÜBINGEN..

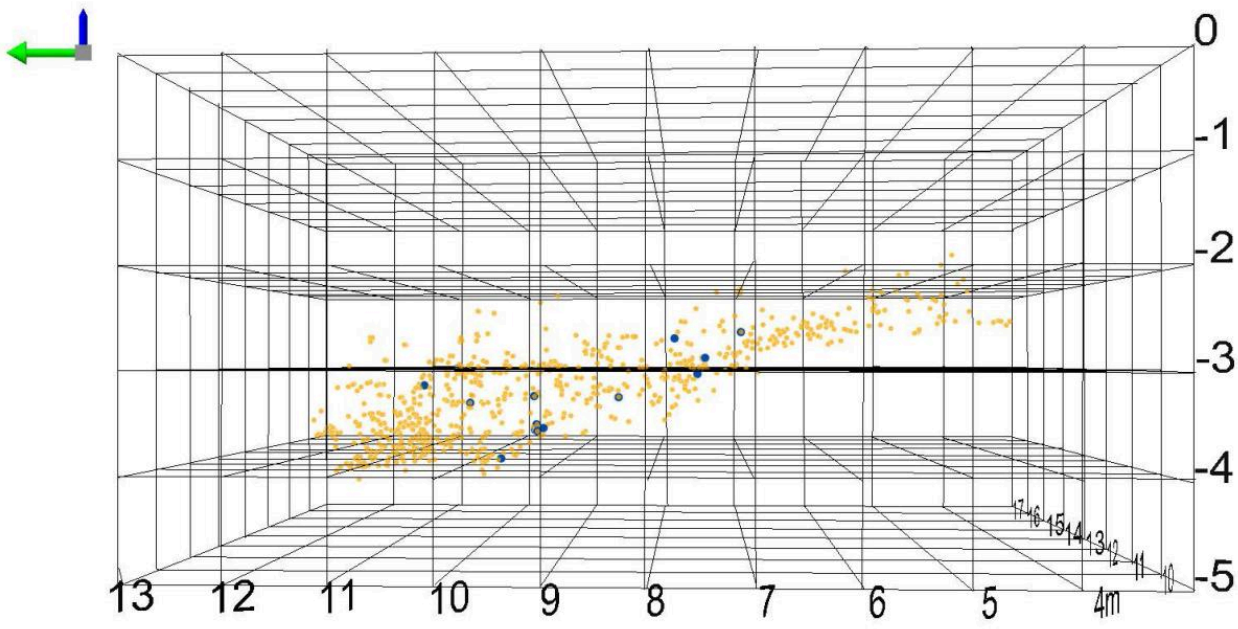

FIG 4. HOHLE FELS, ALL SINGLE FINDS MADE FROM MAMMOTH IVORY (> 1CM, IN YELLOW) AND BEVELLED ARTEFACTS OF THE AURIGNACIAN HORIZONS MENTIONED IN THE ARTICLE (IN PURPLE) (PLOT: VIEW TO THE EAST, SOFTWARE ARCGIS). PLOT BY A. JANAS, SHEP TÜBINGEN.

FIG 5. VVOGELHERD, CEMENTUM PIECE FROM A MAMMOTH TUSK (INVENTORY NUMBER VG IV 2474/2479) WITH A DEEPLY ENGRAVED GROOVE. PHOTO BY H. JENSEN, UNIVERSITY OF TÜBINGEN.

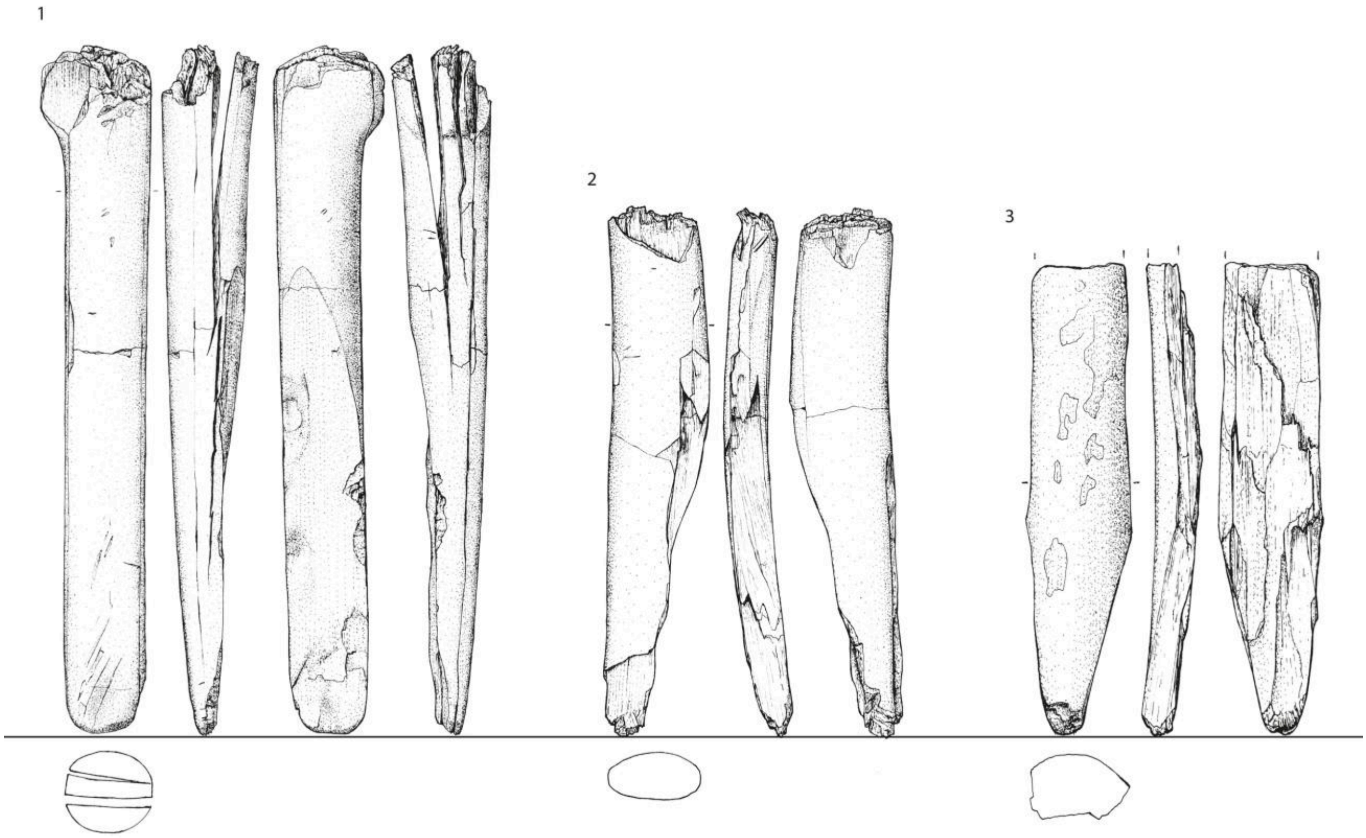

FIG 6. HOHLE FELS, CHISEL 100/2254: FRONT VIEW, REAR VIEW, LATERAL VIEWS; CHISEL 100/2345 AS WELL AS 100/2368/2555: FRONT VIEW, REAR VIEW, ONE LATERAL VIEW, ARCHAEOLOGICAL HORIZON IV. DRAWING: R. EHMANN, © UNIVERSITY OF TÜBINGEN.

FIG 7A. HOHLE FELS, CHISEL N° 100/2345 DETAILS. PROXIMAL END CEMENTUM PART. PHOTO BY S. WOLF, SHEP TÜBINGEN.

FIG 7B. HOHLE FELS, CHISEL N° 100/2345 DETAILS. PROXIMAL END DENTINE PART. PHOTO BY S. WOLF, SHEP TÜBINGEN.

FIG 8. HOHLE FELS (HF) AND GEISSENKLÖSTERLE (GK), AURIGNACIAN BEVELLED ARTEFACTS MADE FROM MAMMOTH IVORY. 1) HF 88/973, AH IIIA; 2) HF 98/204, AH IIIA; 3) HF 25/976, AH VA; 4) HF 99/2044, AH IV; 5) GK 67/1860, AH IIIA; 6) HF 29/1666, AH IV. PHOTOS BY H. JENSEN, UNIVERSITY OF TÜBINGEN.

FIG 9. HOHLE FELS (HF) AND GEISSENKLÖSTERLE (GK), AURIGNACIAN BEVELLED ARTEFACTS MADE FROM MAMMOTH IVORY. 1) HF 25/1198, AH VA; 2) HF 58/1974, AH IIIA; 3) HF 98/1455, AH IV; 4) HF 100/3270, AH VA; 5) GK 77/591, AH III. PHOTOS BY A. FATZ, SHEP TÜBINGEN.

FIG 10. IMPRESSIONS OF THE DIFFERENT WORKING STEPS OF THE EXPERIMENTAL WORK. A) AFRICAN ELEPHANT TUSK PIECE FROM BUNDESAMT FÜR NATURSCHUTZ, B) RÖCK SAWING THE TUSK PIECE INTO TWO HALVES WITH AN ELEKTRA BECKUM BAS 500 METABO GERMANY, C) RÖCK USING AN ELECTRIC HANDPIECE FOR SCRAPING THE BLANKS, D) COMPARISON OF THE BLANK THAT RESEMBLES HF N° 100/2254 (LEFT) AND THE 3D PRINT OF THE ARCHAEOLOGICAL ARTEFACT SERVING AS THE TEMPLATE FOR THE EXPERIMENTAL WORK (RIGHT), E) WORK SITUATION AFTER ACTION N° 2 (POUNDING ON A FLAT PLATE) WITH OBJECT N°1, F) WALTER DURING ACTION N° 3 (STRIKING/HITTING ON THE PROXIMAL SURFACE OF THE EXPERIMENTAL IVORY OBJECT N°2 THAT RESEMBLES ARTEFACT N° 100/2345) ON IVORY. PHOTOS BY K. KITAGAWA.

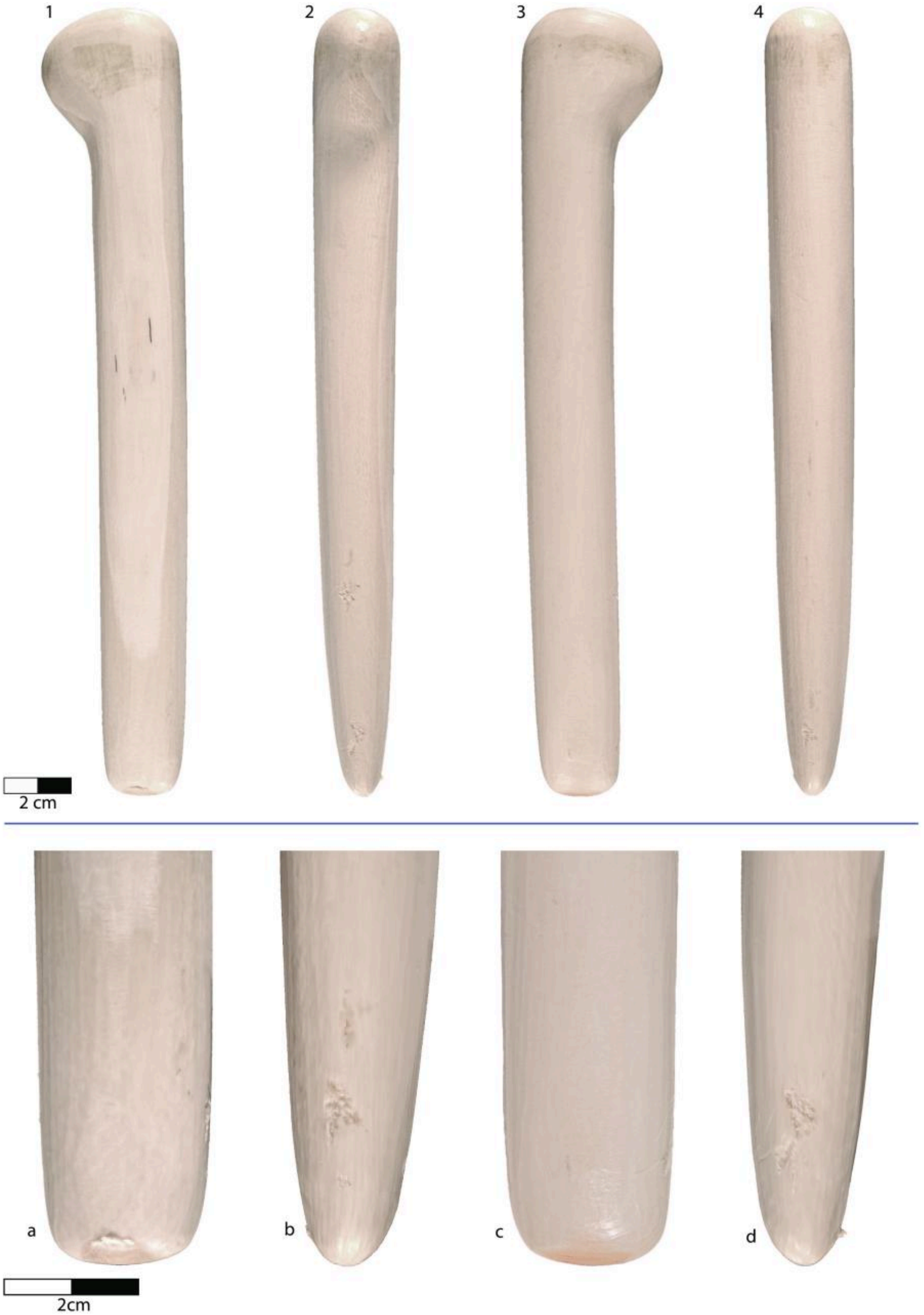

FIG 11. EXPERIMENTAL OBJECT N°1 MADE FROM AFRICAN ELEPHANT IVORY THAT RESEMBLES THE ARTEFACT FROM HOHLE FELS N° 100/2254 AFTER USE. 1) VIEW ON CONVEX SIDE, THE PERIPHERY OF THE TUSK PIECE (CEMENTUM), 3) VIEW ON CONCAVE SIDE, DENTINE PART OF THE TUSK PIECE. ON THE BOTTOM: A)- D) DETAILED VIEWS ON THE DISTAL PART OF THE OBJECT N°1 AFTER USE. PHOTOS BY A. FATZ, SHEP TÜBINGEN.

FIG 12. EXPERIMENTAL OBJECT N°1 MADE FROM AFRICAN ELEPHANT IVORY THAT RESEMBLES THE ARTEFACT FROM HOHLE FELS N° 100/2254, TOP VIEW ON THE PROXIMAL END. 1) FINAL OBJECT READY TO BE USED, 2) AFTER ACTION N°1 (PESTLE ON A FLAT PLATE), 3) AFTER ACTION N°2 (POUNDING ON A FLAT PLATE), 4) AFTER ACTION N° 3 (STRIKING/HITTING ON THE PROXIMAL SURFACE), 5) AFTER ACTION N° 4 (HAMMERING ON ONE POINT ON THE PROXIMAL SURFACE). PHOTOS BY A. FATZ, SHEP TÜBINGEN.

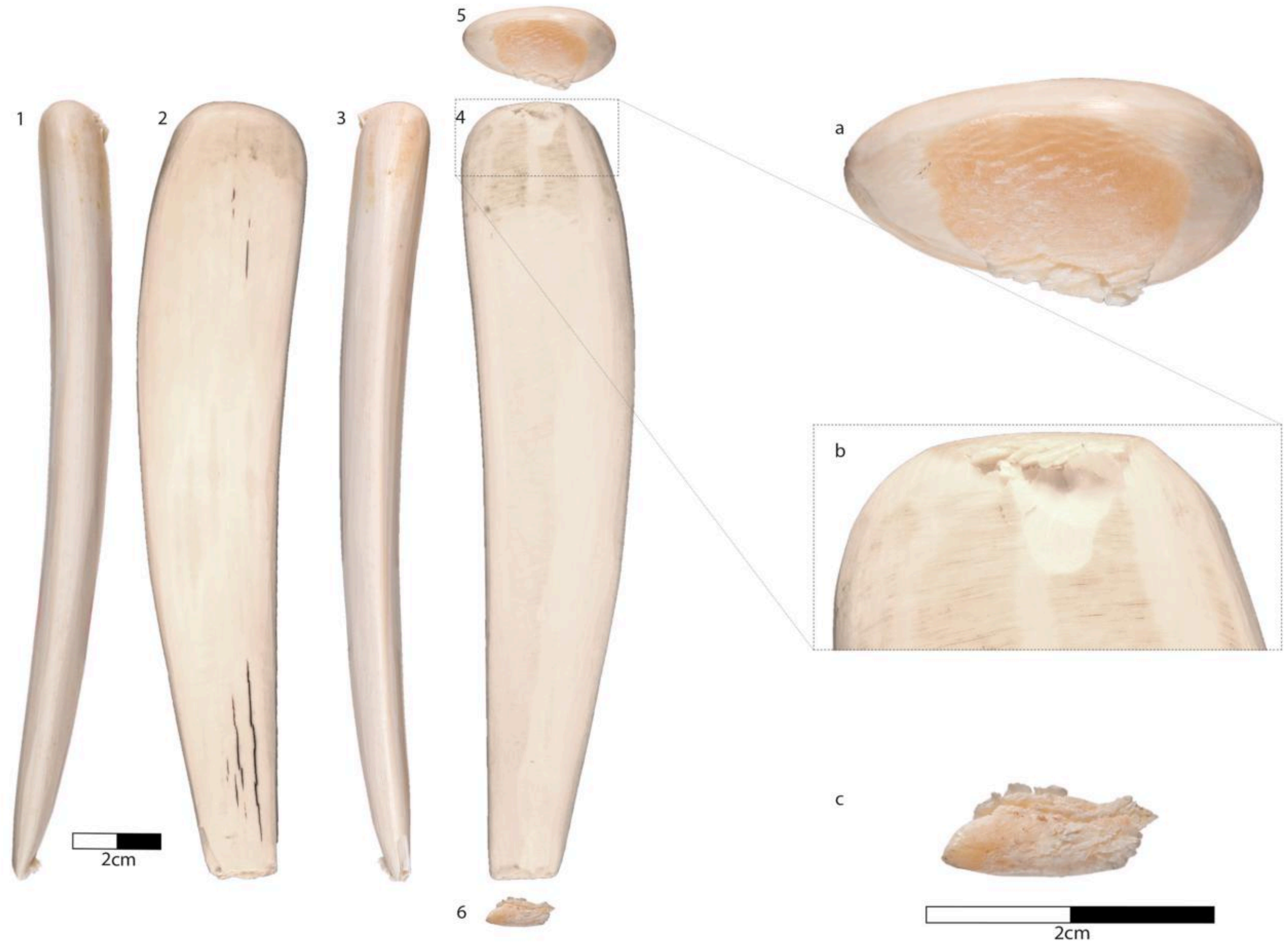

FIG 13. EXPERIMENTAL OBJECT N°2 MADE FROM AFRICAN ELEPHANT IVORY THAT RESEMBLES THE ARTEFACT FROM HOHLE FELS N° 100/2345 AFTER USE. 1) AND 3) LATERAL VIEWS, 2) FRONT VIEW ON CONVEX SIDE, THE PERIPHERY OF THE TUSK PIECE (CEMENTUM), 4) REAR VIEW ON CONCAVE SIDE, DENTINE PART OF THE TUSK PIECE, 5) TOP VIEW ON THE PROXIMAL END, 6) TOP VIEW ON THE DISTAL END, A) MAGNIFICATION OF 5), B) MAGNIFICATION OF 4), C) MAGNIFICATION OF 6). PHOTOS BY A. FATZ, SHEP TÜBINGEN.

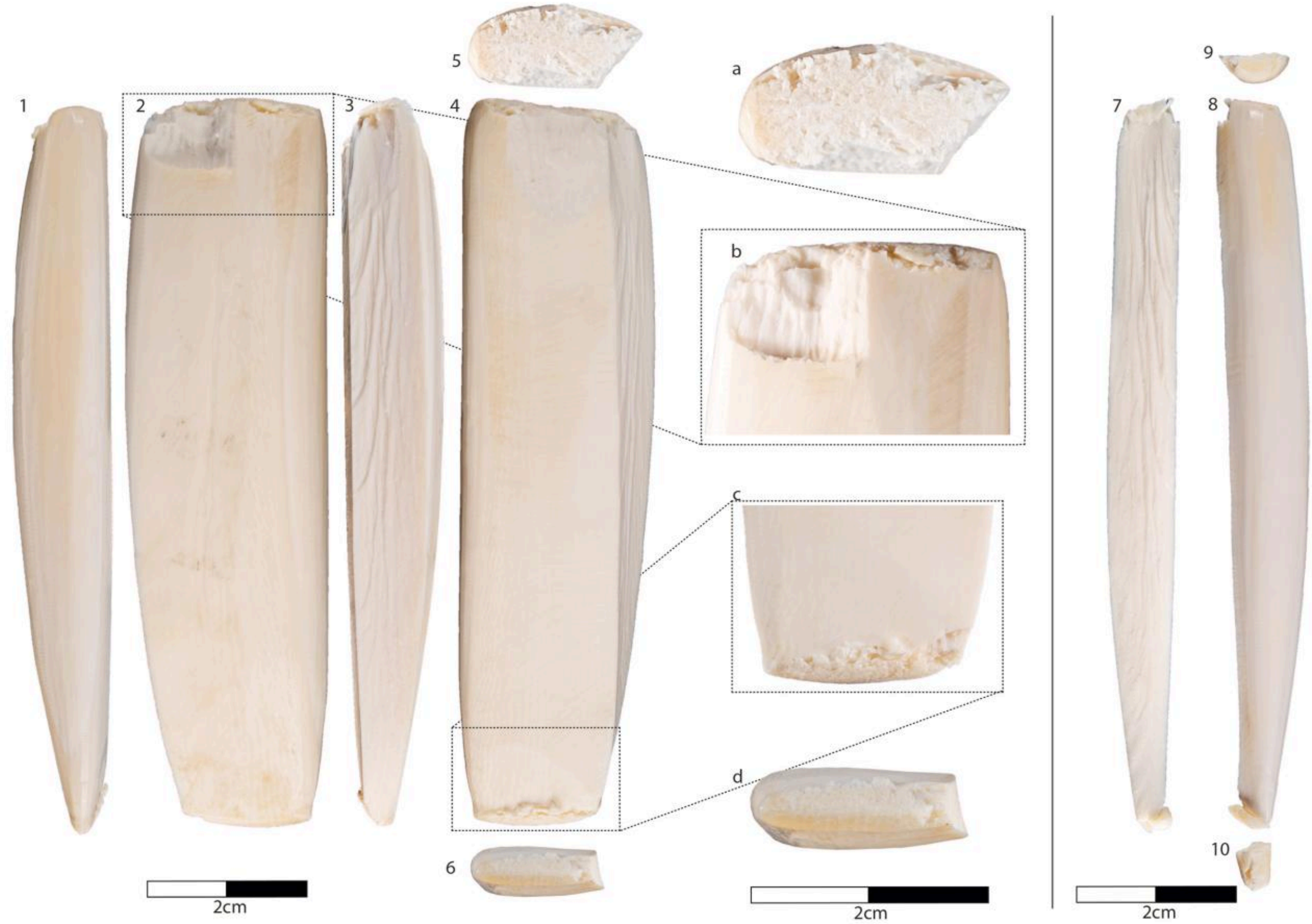

FIG 14. EXPERIMENTAL OBJECT N°4 MADE FROM AFRICAN ELEPHANT IVORY THAT RESEMBLES THE ARTEFACT FROM HOHLE FELS N° 100/2368/2555 AFTER USE. 1) AND 3) LATERAL VIEWS, 2) FRONT VIEW ON CONVEX SIDE, 4) REAR VIEW ON CONCAVE SIDE, 5) TOP VIEW ON THE PROXIMAL END, 6) TOP VIEW ON THE DISTAL END, A) MAGNIFICATION OF 5), B) MAGNIFICATION OF 2), C) MAGNIFICATION OF 4), D) MAGNIFICATION OF 6); 7) FRONT VIEW, 8) REAR VIEW 9) TOP VIEW PROXIMAL END) 10) TOP VIEW DISTAL END OF THE SPLINTER THAT JUMPED OFF DURING ACTION N° 4 (HAMMERING ON ONE POINT ON THE PROXIMAL SURFACE). PHOTOS BY A. FATZ, SHEP TÜBINGEN.

FIG 15. COMPARISON BETWEEN THE ARCHAEOLOGICAL ITEM HOHLE FELS N° 100/2345 (ALL A) WITH THE OBJECT MADE FROM AFRICAN ELEPHANT IVORY THAT RESEMBLES THE HOHLE FELS ARTEFACT N° 100/2345 AFTER USE (ALL B). 1) PROXIMAL END, 2) PROXIMAL PART, DENTINE PART, 3) DISTAL END OF THE DENTINE PART, 4) VIEW ON THE LATERAL EDGE OF THE PIECES WHERE THE SPLINTERS JUMPED OFF, 5) TOP VIEW ON THE DISTAL END. PHOTOS BY A. FATZ, SHEP TÜBINGEN.