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Early anthropogenic use of hematite on Aurignacian ivory personal ornaments from Hohle Fels and Vogelherd caves, Germany

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ABSTRACT

The Aurignacian (ca. 43–35 ka) of southwestern Germany is well known for yielding some of the oldest artifacts related to symbolic behaviors, including examples of figurative art, musical instruments, and personal ornaments. Another aspect of these behaviors is the presence of numerous pieces of iron oxide (ocher); however, these are comparatively understudied, likely owing to the lack of painted artifacts from this region and time period. Several Aurignacian-aged carved ivory personal ornaments from the sites of Hohle Fels and Vogelherd contain traces of what appear to be red ocher residues. We analyzed these beads using a combination of macroanalytical and microanalytical methods, including scanning electron microscopy equipped with energy dispersive spectroscopy and Raman spectroscopy. We found that the residue is composed of the iron oxide mineral hematite (Fe_2O_3). Further analyses on associated archaeological sediments by X-ray diffraction revealed the absence of hematite and other iron oxide mineral phases, suggesting that the hematite residues were intentionally applied to the ivory personal ornaments by human agents. These findings have important implications as they represent evidence for the direct application of ocher on portable symbolic objects by early *Homo sapiens* in Europe. Furthermore, our results reveal shared behavioral practices from two key Aurignacian sites maintained over several millennia and illuminate aspects of pigment use and symbolic practices during a pivotal time in the cultural evolution of humans.

1. Introduction

1.1. Pigments and ornaments in the Upper Paleolithic

Early use of earth pigments is viewed by many archaeologists as an important facet of early hominin behavior, from which a range of other equally important behaviors can be deduced: the emergence of language (d'Errico and Henshilwood, 2011; d'Errico et al., 2009), the development of complex cognition and abstract thinking (Nowell, 2010; Wadley, 2010), and the use of symbols for cultural mediation (d'Errico and Henshilwood, 2011; McBrearty and Brooks, 2000; Wadley, 2006). A series of iron oxide–based pigments, collectively referred to as 'ocher,' are some of the most frequently encountered earth pigments in archaeological contexts. Evidence for the presence of ocher extends as far back as ca. 300 ka in southern Africa (Barham, 2002; Watts et al., 2016) and eastern Africa (McBrearty and Tryon, 2006; Brooks et al., 2016, 2018) and ca. 100 ka in the Levant (Hovers et al., 2003; Salomon et al., 2012). The manipulation of earth pigments has played a key role in identifying and interpreting symbolic expression or the ways and mediums in which humans communicated social ideas, constructs, and conventions nonverbally (d'Errico and Henshilwood, 2011;

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Henshilwood and Marean, 2003; Wadley, 2001), in early hominin behaviors.

In Europe, there is early evidence of the presence of red ocher in Neanderthal contexts at ca. 200 ka (Roebroeks et al., 2012) and at ca. 115 ka (Hoffmann et al., 2018), although it is debated whether these isolated occurrences constituted a common Neanderthal behavioral practice. After the arrival of *Homo sapiens* into the continent, the use of mineral pigments for parietal cave art is well documented in the Aurignacian (ca. 42–30 ka) of Western Europe (d'Errico et al., 2016; González-Sainz et al., 2013; Pike et al., 2012; Valladas et al., 2001; Wood et al., 2018). Following the Aurignacian, the Gravettian (ca. 33–24 ka) and Magdalenian (ca. 17–12 ka) periods contain evidence of ocher use in a variety of forms, including as paint in parietal and portable art (Hradil et al., 2003; Gialanella et al., 2011), as residue on personal ornaments (Poplin, 1972; Albrecht et al., 1983), on processing tools, or on stones in general (Couraud and Bahn, 1982; Conard and Floss, 1999, 2001; Floss and Conard, 2001; Velliky et al., 2018), and associated with burial contexts (Pettitt et al., 2003; Trinkaus and Buzhilova, 2012; Román et al., 2015).

In Central Europe, however, no painted portable or parietal art containing mineral pigments is reported until the Magdalenian (Conard and Floss, 1999, 2001; Floss and Conard, 2001). There is one possibly painted limestone fragment from the Aurignacian at the cave of Geißenklösterle in southwestern Germany (Hahn, 1988), but the orientation and morphology of the pigments warrants further investigation to confirm its anthropogenic origins. This lack of painted art is not due to the absence of humans, who lived in this area not having access to ocher. A recent study found almost 900 ocher pieces and a Gravettian ocher grindstone at the cave site of Hohle Fels in the Swabian Jura region of southwestern Germany (Velliky et al., 2018). The apparent absence of painted objects is also not due to a lack of technological or artistic capacity. Several animal and anthropomorphic figurines (Conard, 2003, 2009), musical instruments (Conard and Malina, 2008; Conard et al., 2009), and hundreds of personal ornaments in the form of beads carved from mammoth ivory are reported from the Swabian Jura that date to a particularly early emergence of the Aurignacian (ca. 43–35 ka) in this region (Conard and Bolus, 2008; Higham et al., 2012). The ivory beads in particular show a unique typology that began in and is characteristic of this region (Conard and Bolus, 2006; Wolf et al., 2013). These assemblages offer evidence for well-established symbolic behavioral practices and cultural complexity not seen in Europe before this time period.

The possible presence of anthropogenically applied pigments on some of the symbolic artifacts from the Swabian Jura was originally observed by Hahn (1986), who discussed traces of red colorants found on several ivory figurines from Vogelherd and Geißenklösterle. However, no further analytical studies were conducted on these artifacts to confirm if the colorants were indeed anthropogenically applied by confirming the presence of specific iron oxide phases, such as hematite, while simultaneously ruling the possibility that the colorants are the result of natural processes (such as iron leeching or staining in the associated sediments). Hahn (1986) proposed that either the residues are likely the product of postdepositional processes or the residues were applied by humans, either for functional (polishing) or esthetic reasons. If the latter is to be confirmed, the ways in which central European Aurignacian populations were using ocher and mineral pigments for personal ornaments might be unique to this region.

Here, we present a study of ocher residues on personal ornaments from the Central European Aurignacian. The personal ornaments are beads carved from mammoth ivory from the sites of Hohle Fels and Vogelherd in the Swabian Jura. The sites found here have yielded some of the earliest evidence (ca. 43 ka) for the arrival of anatomically modern humans into central Europe (Conard and Bolus, 2015). Our main goal is to determine if the residues on the Aurignacian ivory beads contain iron oxide mineral phases (ocher). Our secondary goal is to then investigate the iron oxide content of the associated archaeological sediments to determine whether the residues result from postdepositional processes. If the sediments are devoid of iron oxides, the most likely interpretation is that the residues are the result of anthropogenic actions.

1.2. Archaeological background

The Swabian Jura is a limestone plateau located in southwestern Germany in the present-day state of Baden-Württemberg. It borders the Neckar Valley to the north and the Danube River to the south, and of the Danube's many tributaries, two are particularly rich in archaeological sites—the Ach and Lone valleys. These sites have been of archaeological interest since the late 1800s (Fraas, 1862, 1872). Most of the known sites contain both Middle and Upper Paleolithic deposits and are particularly rich in Aurignacian sediments (Fig. 1; Conard, 2011; Conard and Bolus, 2006, 2008; Conard et al., 2012).

The Aurignacian assemblages from these sites are among the earliest material evidence of the technocomplex in Europe: they date to ca. 43–35 ka (Conard and Bolus, 2003, 2008; Conard, 2009; Higham et al., 2012). Two caves in the Swabian Jura have yielded an exceptionally high number of Aurignacian personal ornaments: Hohle Fels and Vogelherd. Hohle Fels was first excavated in 1870–1871 (Fraas, 1872) and has yielded a relatively intact Aurignacian stratigraphic sequence dating to 43–35 ka. The Vogelherd Cave was discovered in 1931 and then excavated by Gustav Riek in the same year. Within one 10-week period, Riek (1934) and his team excavated almost all of the intact sediments from the cave and discovered a large amount of archaeological materials dating to the Middle and Upper Paleolithic.

Ocher pigments A recent systematic assessment revealed almost 900 individual ocher pieces from the entire Upper Paleolithic sequence (ca. 43–12.5 ka) at Hohle Fels, with 373 pieces (42.7% of total assemblage) originating from Aurignacian contexts (Velliky et al., 2018). Although the Aurignacian has the highest number of individual pieces, only one piece (#87.271) from this period bears evidence of anthropogenic modification, compared with the other 27 modified ochers from the Gravettian and Magdalenian. This is the only modified piece of yellow ocher from the assemblage, but there is currently no evidence of yellow-colored pigments on any artifacts. The type of modification on this piece (two precise incisions) is typically not associated with the production of pigment as it produces very little powder compared with grinding or pulverizing (Hodgskiss, 2010; Rifkin, 2012). These observations thus make a robust interpretation of the Aurignacian ocher assemblage difficult. The total amount of pieces and their variety speak to intensive collection strategies and high demand. However, the low evidence for anthropogenic modification suggests that either ocher was not used as intensively as in later time periods or Aurignacian peoples had different ocher practices surrounding processing and use than Gravettian and Magdalenian populations at the sites. No comprehensive studies have been conducted on the mineral pigment assemblage from Vogelherd, although several ocher pieces ($n = 21$) are currently documented from the older and recent excavations (Velliky, 2019). Visual examples of ocher from Vogelherd and the Hohle Fels Aurignacian are shown in Figure 2.

Aside from ca. 900 reported ocher pieces, some 256 materials are reported to bear traces of possible red ocher residues from the Upper Paleolithic sequence at Hohle Fels. Natural processes likely stained many of these artifacts, as in the case for most of the 104

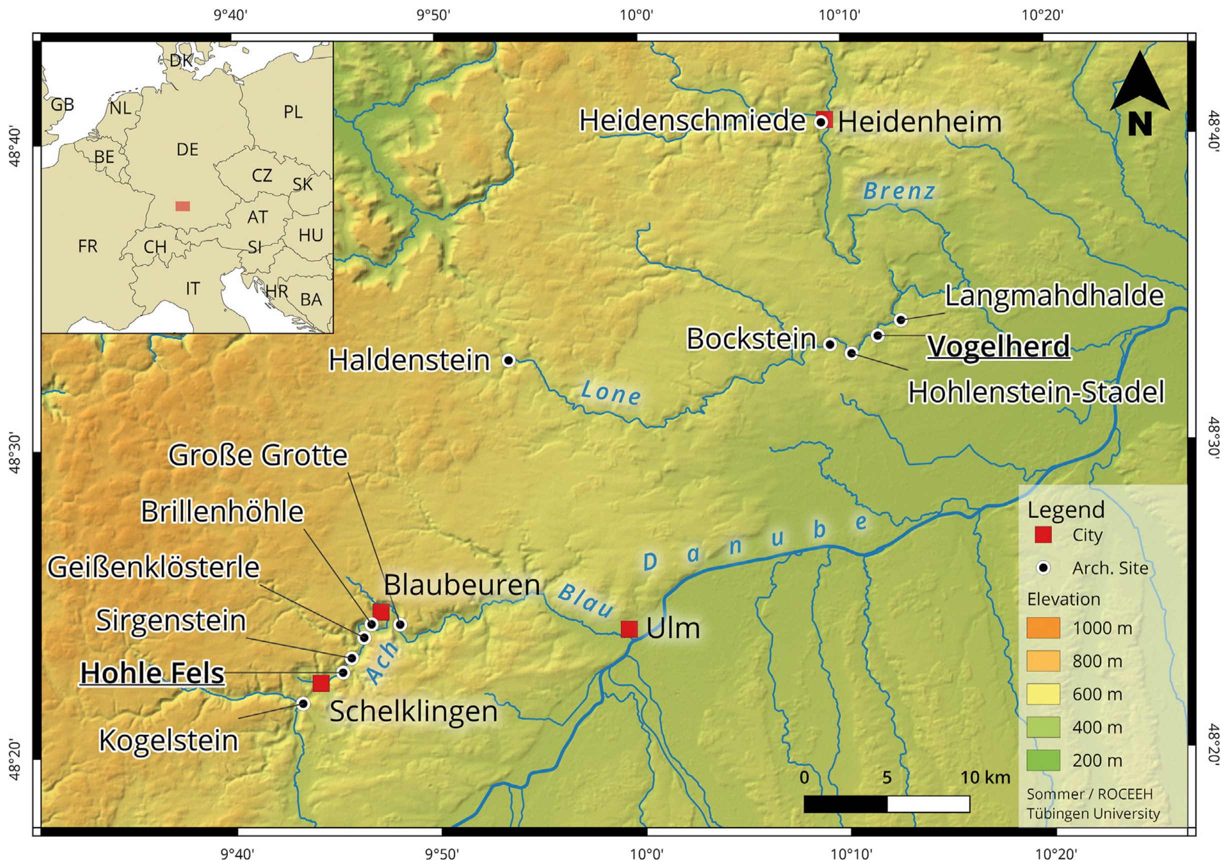

Figure 1. Map of noteworthy Middle and Upper Paleolithic cave sites located in the Swabian Jura of southwestern Germany. Map courtesy of C. Sommer, University of Tübingen (https://doi.org/10.5281/zenodo.3460300).

pieces of limestone that show red coloration (most likely owing to weathering or surface oxidization processes). However, six of these limestone pieces date to the Magdalenian and bear intentionally painted red ocher on their surfaces in rows of painted dots (Conard and Malina, 2010, 2011, 2012). The red residues on these painted limestones represent a style that is unique to southern Germany; currently, similar pieces have only been found at the Klausenhöhle cave sites in Bavaria (Huber and Floss, 2014). In addition, other ocher-stained artifacts attest to how people deliberately used ocher pigments at the cave site. Bones, shells, fossil mollusks, pieces of ivory, animal teeth, and personal ornaments are all examples of material types that bear red colorants (Velliky et al., 2018).

Personal ornaments The Vogelherd Cave has yielded the highest number of Aurignacian-aged beads of the Swabian Jura cave sites ($n = 346$). Riek, 1934 did not report any ivory beads from the original excavations, which is not surprising considering the speed with which he dug through the cave sediments. Between 2005 and 2012, N. Conard from the University of Tübingen excavated the back-dirt from Riek's original excavations and revealed 346 beads that had been missed by Riek (Wolf, 2015b). Excavations at Geißenklösterle and Hohle Fels caves uncovered 235 Aurignacian personal ornaments carved from mammoth ivory with a secured stratigraphic provenance (Hahn, 1988; Wolf, 2015b). Of these, 18 pieces are from the Aurignacian layers II and III at Geißenklösterle, 17 of which are the classic double-perforated form, the other being a single-perforated bead. From Hohle Fels, some 217 beads have been recovered from the Aurignacian layers IId to Vb, and currently 42 are reported from the Gravettian layers (Kölbl and Conard, 2003). Of the Aurignacian beads, 124 (ca. 57%) are the double-perforated form. Other forms include single-perforated beads, basket shapes, nonperforated beads, constricted beads, ring shapes, figure-eight shapes, discoid beads, and a unique triple-perforated bead form that currently has no other known parallel (Wolf, 2015b). However, the double-perforated form is by far the most frequent bead type found in the Aurignacian among the cave sites in the Swabian Jura and has only been found in this region of Europe (Wolf, 2015a, b).

Mammoth ivory was also a medium for personal ornaments in the Gravettian, although on a smaller scale, and was dominated by teardrop shapes and basket forms also found in Bavaria and Poland (Vercoutère and Wolf, 2018). During the Gravettian, mammoth ivory remained the preferred raw material for carving personal ornaments, although its use in general in the Swabian Jura decreased (Wolf et al., 2016; Münzel et al., 2017) and was subsequently replaced by other faunal elements, such as animal teeth (Camarós et al., 2016).

2. Materials and methods

A systematic assessment of the ivory personal ornaments recovered from the Swabian Jura cave sites (Wolf, 2015b) revealed the presence of red colorants on 39 of the Aurignacian and Gravettian-aged ivory beads. Of these, 17 of the beads are from Vogelherd (Fig. 3), which constitute 4.6% of the total assemblage of ivory personal ornaments ($n = 346$). A further 22 are from Hohle

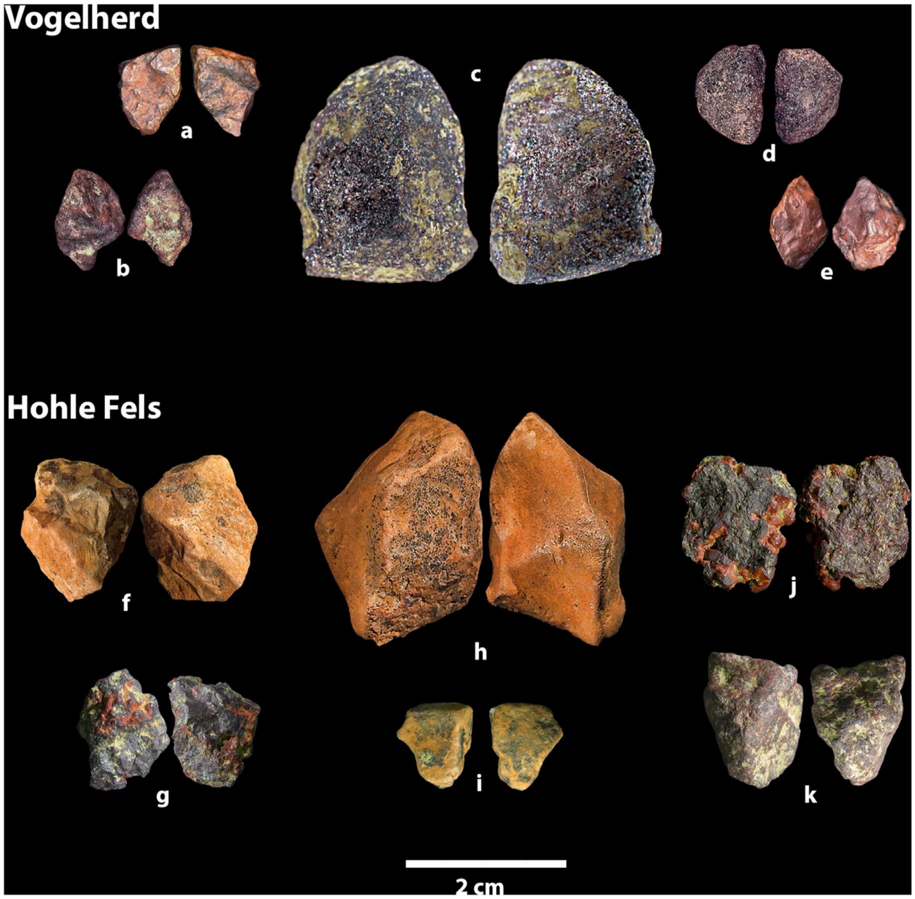

Figure 2. Selection of ocher pieces from Vogelherd and the Hohle Fels Aurignacian. The artifact numbers are: a) 4.1; b) 2.2; c) 5.3; d) 2.1; e) 4.2; f) 97.IIIa.1.1054; g) 55.IIIa.1388; h) 99.IId-IV.2087; i) 66.IIIa-V.4347; j) 54.IIIa.363; k) 29.IId.1489. Note that the Vogelherd ochers do not have a stratigraphic association and are given arbitrary artifact numbers for classification.

Fels (Figs. 4 and 5), with 19 from the Aurignacian layers (ca. 8.8% of total Aurignacian bead assemblage, $n = 217$) and three from the Gravettian (ca. 6.8% of total Gravettian bead assemblage, $n = 44$). All of the ivory beads from Vogelherd were found during the recent re-excavations of the back-dirt left over from the original archaeological excavation in 1931 (Riek, 1934; Wolf, 2015b). Although their provenance is uncertain, we consider these beads to be Aurignacian based on the identification of stylistically and typologically similar ivory beads found during the original excavation (see also Wolf, 2015a, b). Table 1 shows recent radiocarbon dates for the Aurignacian and Gravettian layers at both sites, as well as the number of associated ivory personal ornaments per stratigraphic layer.

We observed the beads using a Keyence VHX900 digital microscope at varying magnifications (5–100×). Six of the beads were selected for further analysis by scanning electron microscopy and energy dispersive X-ray spectrometry (SEM-EDS) to identify traces of iron in the residues. For SEM-EDS analysis, we used a Phenom XL desktop scanning electron microscope from Thermo Fisher Scientific with a field emission gun source. All beads were investigated at 15 KeV in low-vacuum mode (pressure = 60 Pa). Three beads were selected for Raman spectroscopic analysis. The Hohle Fels beads were selected based on their stratigraphic provenance, with one bead from the early Aurignacian (AH: Vab) and one from the late Aurignacian (AH: IIIa) layers. We used a Horiba Jobin Yvon HR800 spectrometer equipped with an edge filter, an exciting wavelength at 458 nm from an Ar^+ laser and a 600 lines/mm grating resulting in a spectral resolution of ≈ 3 cm^{-1}. Spectra were recorded between 2350 and 80 cm^{-1}. Spectrometer calibration was set using the 520.5 cm^{-1} band of a Si crystal. Measurements were made non-invasively and directly on the beads with a 50× or a 100× long working distance objective. The effective laser power at the exit of the objective was lower than 100 μW. Acquisition times for spectra ranged between 40 s and 6 min. Spectra were minimally treated with only a correction of the ripples from the edge filter and a baseline removal (to remove the fluorescence background). No smoothing was applied.

As part of the excavation protocol at Hohle Fels, sediment samples were taken from every 3 cm spit in two opposite corners of the 50 × 50 cm excavation quadrant. We located six sediment samples from the Aurignacian layers at Hohle Fels for analysis using X-ray diffraction (XRD). The sediment samples are contextually associated with two of the beads that were investigated (Fig. 4a, #25.1310.2; Fig. 5d, #89.1211) and serve as a proxy for the type of Fe-mineral phase present in the site's sediments. Vogelherd has not received any intensive micromorphological or sedimentological analyses owing to most of the modern excavations having been conducted in the disturbed back-dirt of older excavations.

For analysis by XRD, the sediment samples were first dried, then ground in an agate mortar and pestle, and mounted in standard steel sample holders. The instrument is a Bruker D8 ADVANCE ECO XRD scanner configured with linear detector SSD 160 and a 2.2 KW Cu fine focus cathode tube operating at 40 kV and 25 mA, using Cu-

Figure 3. Ivory beads from the Vogelherd Aurignacian containing red residues. The bead artifact numbers are: a) 38/74.59.1; b) 37/68.17.1; c) 38/72.89.1; d) 45/70.62.1; e) 36/73.6.1; f) 36/71.41.1; g) 35/72.34.1; h) 44/70.66.1; i) 36/75.105.1; j) 43/69.50.1; k) 39/71.98.1; l) 43/69.26.1; m) 43/70.28.1; n) 36/78.38.1; o) 39/67.70.1; p) 35/70.63.1; q) 38/76.72.1.

Table 1
Dates for the Hohle Fels and Vogelherd Aurignacian and Gravettian, with bead totals per layer. Calibrated radiocarbon dates showing maximum and minimum age for corresponding archaeological horizons at Hohle Fels and Vogelherd. All dates calibrated with CalPal-Hulu. Note that six beads from the Hohle Fels Aurignacian came from profile cleanings and are not represented in the total.

AH	Period	Site	Bead totals (n)	Calibrated date	References
IIb	G	HF	12	32,725 ± 319–31,390 ± 242	Conard and Moreau (2004); Münzel et al. (2011); Kölbl and Conard (2003)
IIc	G	HF	17	34,491 ± 164–30,959 ± 416	Conard and Moreau (2004); Münzel et al. (2011); Kölbl and Conard (2003)
IIcf	G	HF	13	32,622 ± 305–32,244 ± 254	Conard (2003); Münzel et al. (2011); Kölbl and Conard (2003)
IId/IIe	A/G	HF	11	34,795 ± 322–33,884 ± 320	Conard and Bolus (2003); Wolf (2015a, b)
IIIa/b	A	HF	20	36,720 ± 255–35,780 ± 175	Bataille and Conard (2018); Wolf (2015a, b)
IV	A	HF	87	39,010 ± 924–38,970 ± 672	Bataille and Conard (2018); Wolf (2015a, b)
Va/ab	A	HF	75	41,260 ± 579–40,250 ± 363	Bataille and Conard (2018); Wolf (2015a, b)
Vb	A	HF	18	44,170 ± 811–41,300 ± 473	Bataille and Conard (2018); Wolf (2015a, b)
IV	A	VH	n/a	36,173 ± 466–35,010 ± 684	Conard and Bolus (2003, 2008); Wolf (2015a, b)
V	A	VH	n/a	40,554 ± 1057–34,578 ± 1361	Conard and Bolus (2003, 2008); Wolf (2015a, b)

Abbreviations: AH = archaeological horizon; G = Gravettian; A/G = Aurignacian/Gravettian transition; A = Aurignacian; HF = Hohle Fels; VH = Vogelherd.

Kα radiation (1.54060 Å). Each sample was measured using a monochromatic X-ray beam and scanned from 2.5° to 90° 2Θ at a scanning step size of 0.02° (2Θ). XRD measurements were carried out using DIFFRAC.SUITE software, and qualitative phase analysis was conducted using the DIFFRAC.EVA PDF-4+ database (Gražulis et al., 2009, 2011).

3. Results

3.1. Bead morphology and use-wear

Of the beads from Vogelherd, the majority (15 of 17; Fig. 3) bear the classic double-perforated form and range from 13 to 7 mm in size (on the long axis). Of the two beads not of this style, one has

Figure 4. Ivory beads from the Hohle Fels Aurignacian (ca. 43–35 ka) containing red residues. The bead artifact numbers are: a) 25.1340.2; b) 77.1789.1; c) 1890.2; d) 89.1578.2; e) 25.1340.9; f) 10.1044.2; g) 31.175; h) 25.1354.2; i) 27.1011.1; j) 25.1340.12; k) 27.1983.1; l) 25.1161.1; m) 76.1510.1; n) 25.1340.8; o) 29.1890.1; p) 25.1340.1; q) 25.1307.

Figure 5. Ivory beads from the Hohle Fels Gravettian and late Aurignacian containing red residues. The Gravettian (ca. 34–30.5 ka) beads (a–c) show clear stylistic diversity from the Aurignacian beads. One bead (d) dates to the late Aurignacian (layer IIIa). The bead artifact numbers are: a) 110.1279; b) 66.749; c) 57.1499; d) 89.1211.

two perforations but also bears a wedge-shaped appendix (Fig. 3h). The last is also a double-perforated bead but contains incised decorations along the outer ridge (Fig. 3k). From Hohle Fels, 18 beads date to the Aurignacian (Figs. 4 and 5d), ranging in length from 22 to 7 mm, and all except for two are the double-perforated form. The other two are a figure-eight shape (Fig. 4i) and a basket shape (Fig. 5d). A further three beads are from the Gravettian and are ca. 29 to 18 mm long (Fig. 5a–c). All of the beads from both Vogelherd and Hohle Fels contain varying amounts of red residues, but in all of the samples, the red residue is almost exclusively contained within the perforations, and in most cases on both sides of the artifacts. Although it is common practice to use photo-enhancement software for observing color pigments on surfaces and artifacts, image processing did not show a significantly better result than microscopic observations to highlight the presence/distribution of pigments. Descriptions of the beads and their stratigraphic provenance are summarized in Tables 2 and 3 (Vogelherd and Hohle Fels, respectively).

The beads we report on in this article display a variety of use-wear intensities: some show evidence for being heavily worn with intense smoothing and polish around the interior of the perforations (Figs. 3o, q, 4a, b, d, g, o, p, and 5a–d; Supplementary Online Material [SOM] Fig. S1); others appear to not have been worn at all, bearing irregularly shaped perforations with no evidence of polish or smoothing (Figs. 3e, i, l–n, p, and 4m, q; SOM Fig. S2). Some are not entirely completed, as seen in the pieces where one side shows a completed perforation and the other side is flattened with a smaller perforation, or without one entirely (Figs. 3f and 4f). The latter two tend to bear similar traits in their perforations. To date, there has been no systematic assessment of the use-wear on the total bead assemblage from the Swabian Jura, and we can therefore not directly compare the use-wear evidence observed on these beads with the wider assemblage. Our observations on the beads bearing hematite residues are consistent with types of use-wear reported on elsewhere, including polish and superficial smoothing (d'Errico, 1993; Falci et al., 2019; Vanhaeren et al., 2013).

Table 3
Artifact list of ivory beads from Hohle Fels Aurignacian and Gravettian. The table includes artifact description, provenance (archaeological horizon, dates of which are shown in Table 1 in text), and the types of analysis used.

Sample no.	Description	Provenance	Period	Figure	Analysis
25.1340.2	Double perforated	Vab	A	Figure 4a	M, S
77.1789.1	Double perforated	IV	A	Figure 4b	M
1890.2	Double perforated	Vab	A	Figure 4c	M
89.1578.2	Double perforated	IV	A	Figure 4d	M
25.1340.9	Double perforated	Vab	A	Figure 4e	M
10.1044.2	Double perforated	Va	A	Figure 4f	M
31.175	Double perforated	Vab	A	Figure 4g	M
25.1354.2	Double perforated	Vab-VII	A	Figure 4h	M, S
27.1011.1	Figure-eight-shape	Va	A	Figure 4i	M, S
25.1340.12	Double perforated	Vab	A	Figure 4j	M
27.1983.1	Double perforated	Vaa	A	Figure 4k	M
25.1161.1	Double perforated	Vaa	A	Figure 4l	M
76.1510.1	Double perforated	IV	A	Figure 4m	M
25.1340.8	Double perforated	Vab	A	Figure 4n	M, S
29.1890.1	Double perforated	Vab	A	Figure 4o	M
25.1340.1	Double perforated	Vab	A	Figure 4p	M
25.1307	Double perforated	Vab	A	Figure 4q	M
25.1310.2	Double perforated	Vab	A	Figure 4r	M, R
110.1279	Tear-drop-shape	IIcf	G	Figure 5a	M
66.749	Tear-drop-shape	IIc	G	Figure 5b	M
57.1499	Tear-drop-shape	IIc	G	Figure 5c	M
89.1211	Basket-shape	IIIa.1	A	Figure 5d	M, R

Abbreviations: G = Gravettian; A = Aurignacian; M = macroscopic; S = scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS); R = Raman spectroscopy.

3.2. Scanning electron microscopy with energy dispersive spectroscopy

The results of the SEM-EDS analyses are shown in Figure 6 and Table 4. In the backscattered electron images of the beads, accumulations of the residues are seen as platy and cracked within the perforations in the ivory, suggesting that they are added onto the beads after they were carved. We conducted three spot analyses on each of the beads in areas showing moderate traces of residue. The elemental compositions were identified using the energy-dispersive X-ray spectra on each of the spots analyzed. From the spectra, we observed traces of Fe, accompanied in most cases by Si, Ti, and Mg. There were some minor occurrences of Al and Ca.

3.3. Raman spectroscopy

Representative Raman spectra are shown in Figure 7. All three spectra recorded on one Vogelherd and two Hohle Fels beads are similar, showing four sharp bands in the low wavenumber section. The hematite bands near 225, 295, 410, 610, and 1310 cm^{-1} are

Table 2
Artifact list of ivory beads from the Vogelherd Aurignacian. The table includes artifact description and the types of analysis used.

Sample no.	Description	Figure	Analysis
38/74.59.1	Double perforated	Fig. 3a	M
37/68.17.1	Double perforated	Fig. 3b	M
38/72.89.1	Double perforated	Fig. 3c	M,
45/70.62.1	Double perforated	Fig. 3d	M
36/73.6.1	Double perforated	Fig. 3e	M
36/71.41.1	Double perforated (half-product)	Fig. 3f	M, S
35/72.34.1	Double perforated	Fig. 3g	M
44/70.66.1	Double perforated with a wedge-shaped appendix	Fig. 3h	M
36/75.105.1	Double perforated	Fig. 3i	M
43/69.50.1	Double perforated	Fig. 3j	M, R
39/71.98.1	Double perforated (decorated)	Fig. 3k	M
43/69.26.1	Double perforated	Fig. 3l	M
43/70.28.1	Double perforated	Fig. 3m	M
36/78.38.1	Double perforated	Fig. 3n	M
39/67.70.1	Double perforated	Fig. 3o	M
35/70.63.1	Double perforated	Fig. 3p	M
38/76.72.1	Double perforated	Fig. 3q	M, S

Abbreviations: M = macroscopic; S = scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS); R = Raman spectroscopy.

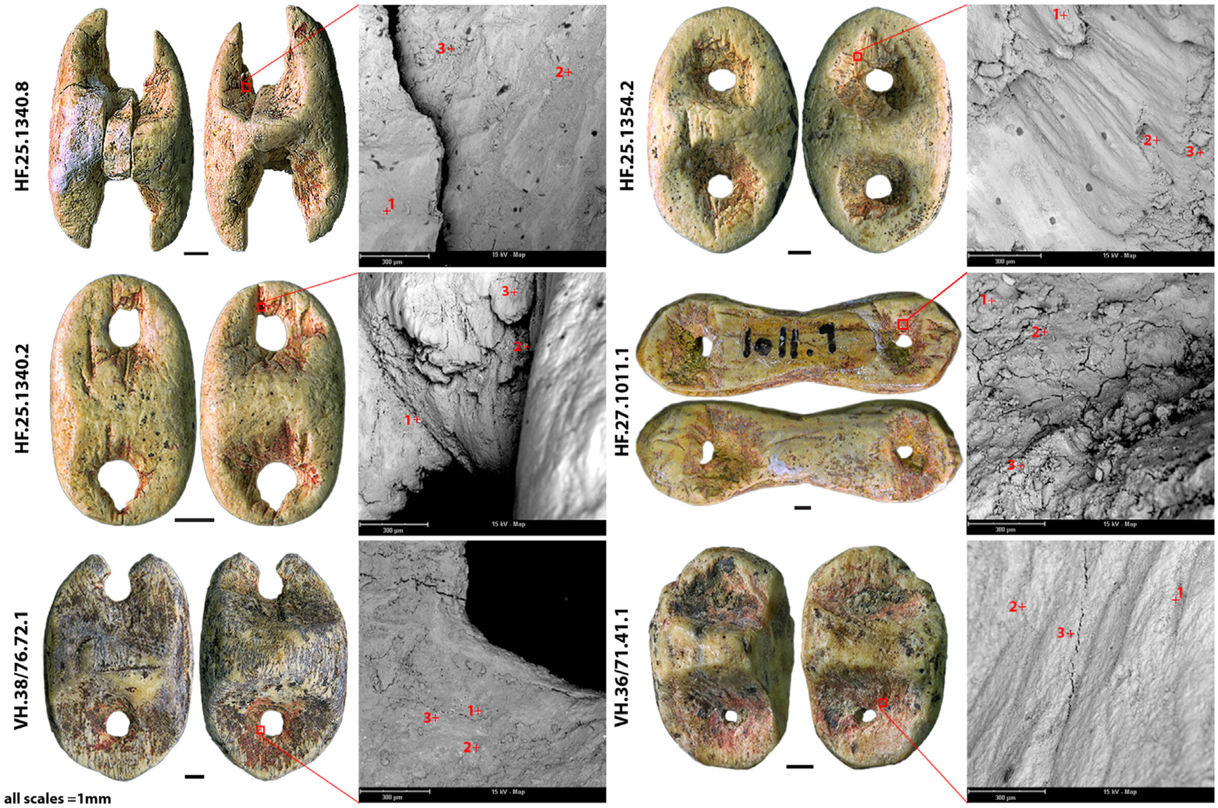

Figure 6. Bead and backscattered electron (BSE) images of selected ivory bead ocher residues from Hohle Fels (HF) and Vogelherd (VH). The BSE images show point of analysis spots, with identified chemical elements shown in Table 2.

Table 4
Results of scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS) on ivory beads showing identified elements for each of the residue spots analyzed. Artifact numbers correspond to Tables 2 and 3.

Bead artifact #	Point of analysis and elements identified		
	1	2	3
HF.25.1340.8	Fe, Si	Fe, Si, Al	Si, Al, Fe
HF.25.1354.2	Fe, Si	Fe, Si, Al	Fe, Si, Al
HF.25.1340.2	Fe, Si, Ti	Fe, Si	Fe, Si, Al
HF.27.1011.1	Si, Al, Fe	Fe, Si, Al	Fe, Si
VH.38/76.72.1	Fe, Si	Fe, Si	Fe, Si
VH.36/71.41.1	Fe, Si, Al	Fe, Si, Al	Fe, Si, Mg

Abbreviations: HF = Hohle Fels; VH = Vogelherd.

present (Lafuente et al., 2015). If the residue had been goethite, α-FeO(OH), the set of vibrational bands present would have been radically different (Binder et al., 2014). By characterizing the mineralogical structure, the vibrational signatures obtained thus unambiguously indicate that the red residues are hematite.

3.4. XRD of sediment samples

We analyzed six sediment samples from Hohle Fels. Two samples are from square 89, layer IIIa, corresponding to bead #89.1211 (Fig. 5d). Another four samples derive from square 24, layer Vb, and square 25, layer Vaa, which are stratigraphically correlated to bead #25.1320.2 (Fig. 4r). Overall, the sediment samples represent a temporal spread of the Aurignacian layers, from the earliest (layer Vb) to the latest (layer IIIa) phases found at Hohle Fels (Table 3). Diffraction patterns consist of a mixture of mainly calcite and quartz, with calcite values ranging from 51% to 83% and quartz values ranging from 17% to 49% (SOM Fig. S3; SOM Table S1). Only a few weak diffraction peaks cannot be explained by these minerals. Applying the DIFFRAC.EVA PDF-4+ database for hematite and goethite to the Hohle Fels sediment diffraction patterns leaves no doubt that none of the two main hematite reflections at 33.1°2θ and 35.6°2θ (104 and 110 in Fe_2O_3, respectively) are present in the sediment samples. The same is true for goethite: both major peaks at 21.3°2θ (101) and 36.8°2θ (111) are absent from the sediment diffraction patterns. Thus, the results of these analyses do not document the presence of the iron phases hematite and goethite in the sediment samples from Hohle Fels.

4. Discussion

4.1. Sample context and chronology

While ivory beads from Hohle Fels are unambiguously dated and represent a continuous sequence from the Aurignacian to the Gravettian (stratigraphic contexts are shown in Table 3), the Vogelherd beads came from the recent re-excavations of back-dirt from Gustav Riek's original excavations in the 1930s (Riek, 1934). We are therefore unable to establish their original stratigraphic position and temporal provenance. It has previously been suggested that their production technique and style is prevalent among Aurignacian beads from the region, suggesting that these artifacts are most likely from this time period, i.e., typologically, they are representative of the Aurignacian cultural complex of the Swabian Jura (Wolf et al., 2013; Wolf, 2015b).

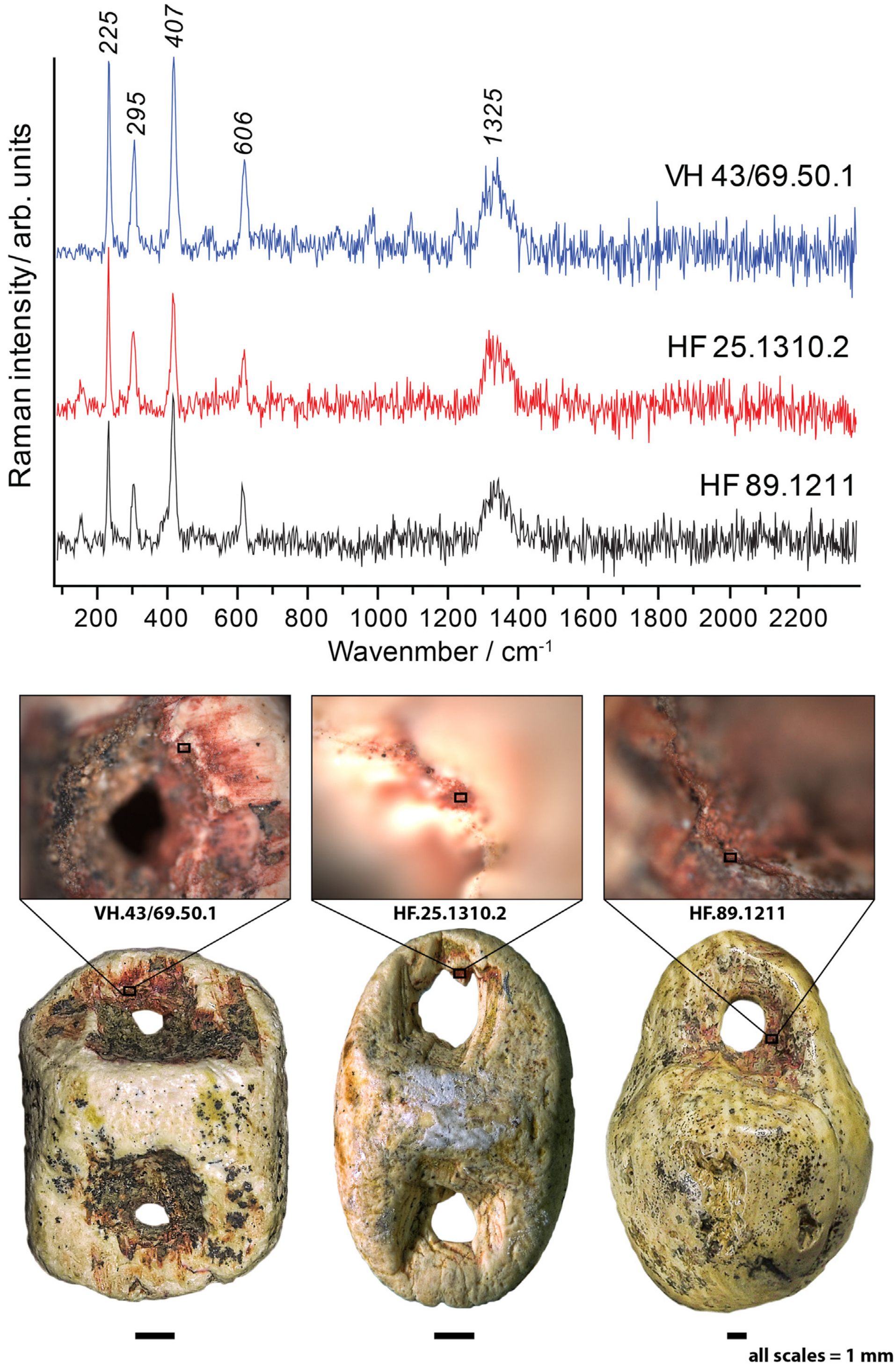

Figure 7. Macroscopic and microscopic view of analyzed points on bead artifacts. The Raman spectra above correspond to each of the analyzed points labeled with artifact numbers, with relevant spectral bands indicated.

All of the beads containing the largest amounts of hematite residue came from Vogelherd. At this point, it remains unclear why the Vogelherd beads contain more residues or preserve hematite residues better than Hohle Fels beads. Micromorphological analyses conducted on the Hohle Fels sediments have shown phases of intense freezing and thawing during the Aurignacian, as well as the movement and redeposition of sediments from the rear of the cave to the current excavation area nearer to the entrance (Miller, 2015). These natural processes, along with water screening and postexcavation processing, may have altered the preservation potential of residues on the ivory beads. In general, many of the Aurignacian-aged sediments in the Lone Valley, and in the Swabian Jura more generally, are well preserved owing to a relatively stable environment (Miller, 2015; Barbieri et al., 2018). The amount of preserved residue could also be a by-product of certain behavioral aspects leading to the deposition of the residues on the beads, or perhaps certain cultural preferences or practices.

4.2. Possible scenarios for ocher residues on ivory beads

The production sequence of Aurignacian ivory beads is well understood for Western and Central European sites (Hahn, 1988; Heckel, 2009; Heckel, 2018; White, 1995; Wolf, 2015a, b; Wolf et al., 2013). To make such beads, precision tools and ca. 15–45 min are necessary. However, the use of pigments, specifically red ocher, during the production of ivory beads has been previously proposed (Heckel, 2009; Nivens, 2020; White, 1993, 1995), but never fully confirmed on artifacts. Our results show that ocher was involved in the chaîne opératoire of ivory bead production; however, there are several possibilities for which specific purposes it was used for.

Previous experimental studies have shown red ocher, and specifically hematite, to be useful for the final stages of ivory bead processing (White, 1993, 1995, 1997). White (1997) suggested that powdered hematite is particularly suitable for polishing beads to create a shiny luster. He also stated that modern ivory workers use metallic abrasives, or 'jeweler's rouge,' when polishing ivory pieces that are essentially powdered iron oxide. Many of the ivory beads found from the Ach and Lone valley cave sites, including Hohle Fels and Vogelherd, are highly polished with a shiny luster (Wolf, 2015b). During bead polishing experiments using steatite (soapstone) and lignite (in place of ivory), Nivens (2020) observed that the most significant factors involved in the efficacy of polishing materials were grain size and mineralogy. Nivens (2020) noted that hematite-rich materials were consistently more effective at polishing beads than goethite, even when artificially created (in this case, by heating goethite to 600 °C). Furthermore, when polishing lignite (which has a similar hardness to ivory), coarse-grained hematite-rich materials (such as hematite-rich sandstone) were the most effective at polishing the beads quickly to render a shiny, lustrous appearance. The results of Nivens' (2020) experiments are in line with the qualitative observations of the ocher assemblage at Hohle Fels cave, where hematite-rich red ochers with sandy textures are most frequent during the Hohle Fels Aurignacian, more so than the later time periods (Velliky et al., 2018). Furthermore, ocher from the later Aurignacian (AH: IIIa) was found to contain protohematite, a metastable phase with a unique structure that may indicate high-temperature thermal exposure (Burgina et al., 2000; Velliky, 2019; Heckel, 2009) noted the usefulness of hematite powder for polishing ivory figurines and states it not only results in a bright, smooth, and generally visually pleasing appearance but also erases shallow tool striae. In addition, from the earlier excavated materials from Vogelherd, Hahn (1986) reported the presence of microscopic red colorants on two figurines (a mammoth and a felid figurine) as well as the 'Adorant' figurine from Geißenklösterle, although their anthropogenic origin is still unconfirmed (Hahn, 1988). The polished luster of many of the Aurignacian-aged ivory figurines from several of the cave sites in the Swabian Jura may suggest that if hematite powder was indeed used for polishing ivory beads, it was also possibly used during the production of the ivory figurines (Hahn, 1986).

Alternatively, the position of the hematite residues on the interior of the perforations, within the natural microfissures in the ivory support, may indicate that the beads were sewn onto ocher-covered clothing or fabric or were strung on strings or hair covered in ocher. The beads we report on from Hohle Fels appear to have been more heavily worn than their Vogelherd counterparts, suggested by the appearance of polish and patina around certain areas, and in general have less visible ocher residue in their perforations (although this is difficult to quantifiably measure). In previous bead polishing experiments, Allard et al. (1997) noted that when use-wear associated with suspension was observed on beads made from antler, these areas were devoid of ocher residues. In the case of ivory beads from Hohle Fels and Vogelherd, there are ocher residues present even on beads with observed polishing, although the heavily worn beads appear to have retained lower amounts of the ocher residues. These observations suggest that either ivory and antler mediums preserve residues differentially, that the ivory beads were in contact with ocher-covered supports, or that hematite was reapplied to the beads after the initial production.

The reapplication of hematite-rich ocher to the beads after production may have been for esthetic, functional, or symbolic purposes. These actions would explain the pattern of ocher pigment removal: red residues are only intact on the bead concavities (surrounding the perforations) and not on external surfaces, which would have eventually 'rubbed off.' Over time, pigments removed from the exterior parts may have progressively accumulated into the beads' concavities.

The aforementioned scenarios are not mutually exclusive, and ocher may have been applied at several stages for different reasons over an extended period of time. The most parsimonious explanation based on the evidence presented here is that the coarse-grained, hematite-rich sandstones that are frequent during the Aurignacian at Hohle Fels were collected and used as polishing materials for the ivory personal ornaments. The predominance of hematite residues within the perforations is consistent with the observations reported from previous experiments using hematite-based polishing materials for beads at a relatively later stage during their production (Allard et al., 1997; White, 1997; Nivens, 2020). Our qualitative assessment of the beads shows that beads with more intensive use-wear around their perforations tend to contain less visible hematite residues, especially for the Gravettian-aged beads (Fig. 5a–c). Based on this assessment, we infer that the beads were likely not sewn on to ocher-covered supports. Finally, we do not rule out the possibility that the use of the hematite-rich ocher may have held other purposes that cannot be explained by functional aspects alone. In light of the collective evidence of ocher use during the European Upper Paleolithic, we believe that ocher was not collected exclusively for this behavioral practice in the Swabian Jura, and may have operated in several capacities, both symbolic and functional, during the Aurignacian at Hohle Fels and Vogelherd.

4.3. The role of ocher and personal ornaments during the Swabian Aurignacian

The Swabian Aurignacian is well known for its mammoth ivory personal ornaments, as well as other figurative art forms and musical instruments made from mammoth ivory (Conard, 2003, 2009; Conard et al., 2009). After the last glacial maximum, the preferred medium changes from mammoth ivory to other forms of faunal elements, including mammoth bones for osseous tools (Münzel, 2001; Münzel et al., 2017; Wolf et al., 2016) and animal teeth for personal ornaments (Camarós et al., 2016). The personal ornaments that are made from mammoth ivory from the Gravettian are different in shape and size (Fig. 5a–c) compared with the small double-perforated bead type that frequents the Swabian Aurignacian. Based on the presence of hematite residues on several ivory personal ornaments from the two cave sites and the numerous pieces of collected ocher, we can infer that ocher pigment powder was indeed created and used by people living in the Swabian Jura during the Aurignacian. Because there are numerous ivory preforms, ivory rods, and debitage, suggesting ivory bead production taking place at both of the cave sites (Wolf, 2015b), it is possible that ocher pigment production and bead production occurred at different locations during the Aurignacian. While the ivory beads were produced inside of the cave, ocher powder was produced elsewhere, then transported to the appropriate places for the final production stages. A similar scenario is proposed by White (1997), who suggested that bead manufacture sites may have been regarded as special places on the landscape, where distant groups may have gathered for trade and exchange.

Changes can also be seen in the ocher assemblage from Hohle Fels: the Aurignacian ochers are high in number ($n = 373$) and show many textural and color varieties, whereas in the Gravettian and Magdalenian, fine-grained, dark red, micaceous hematite-rich ochers are the preferred type and were selectively collected (Velliky et al., 2018). In addition, the Gravettian and Magdalenian at Hohle Fels also show an increase in modified ocher pieces, processing tools, and artifacts with intentional ocher application, such as the painted limestone fragments from the Magdalenian (Scheer, 1994; Conard and Floss, 1999; Floss and Conard, 2001; Conard and Malina, 2010, 2011, 2012, 2014). Currently, no ocher processing tools are reported from the Aurignacian, and there is only one reported anthropogenically modified ocher piece made of yellow ocher (no traces of yellow pigment were observed on the beads). There are currently no reports of hematite or ocher powder in the cave sediments from Hohle Fels, although a so-called 'Rötelschicht' or ocher layer is reported from the nearby site of Geißenklösterle (Hahn, 1988). However, in general, it is likely that microstratigraphic ocher contexts are overlooked or underreported.

Of the other artifacts bearing red colorants at Hohle Fels, 110 date to the Aurignacian. The most frequent material type containing red colorants is limestone ($n = 79$), followed by ivory ($n = 20$), bone ($n = 7$), and other stone ($n = 4$), which in most cases are either lithics made from a locally sourced chert called 'Jurahornstein,' or in some cases sandstone. One material type that is reported with red colorants that is absent in the Aurignacian but frequent in the later time periods is shell, with 29 specimens found in the Gravettian layers and 12 found in the Magdalenian deposits. Almost all of the ivory materials from the Aurignacian that are reported to bear red colorants are personal ornaments, although some personal ornaments made from other faunal elements (such as reindeer teeth) are found in the Gravettian and Magdalenian (Velliky et al., 2018). Because the red colorants on many of the limestones and faunal elements from the Aurignacian were likely the by-product of natural processes, the ivory personal ornaments are the strongest evidence for ocher pigment use during this time period at Hohle Fels.

There are currently no comprehensive studies on the mineral pigment assemblage from Vogelherd, although several ocher pieces are documented from the older and recent excavations ($n = 21$). The Vogelherd ocher assemblage contains mostly hematite-rich, fine-grained micaceous ochers that produce dark red streaks. The 21 pieces have a combined weight of 67.56 g, range from light purple to dark red in exterior color, and do not bear any evidence of anthropogenic modification. Unfortunately, their stratigraphic provenance cannot be assured. Although Hahn (1987) previously reported visible red colorants on some of the ivory figurines found at the site, the ivory beads analyzed in this study form the first definitive evidence of ocher use at the site of Vogelherd.

4.4. Implications for early symbolic behavior

Although the abundance of figurative art from the earliest Aurignacian layers at Hohle Fels suggests that the Swabian Aurignacian was already well developed from its onset (Conard and Bolus, 2006), the majority of personal ornaments come from the early Aurignacian layers IV ($n = 87$) and Va/ab ($n = 75$). Layer Va/ab yielded some 63,689 lithic artifacts (both worked tools and debitage) and 243 ocher pieces, both of which represent the highest number for these artifact types at the site (Velliky, 2019). These layers are dated to ca. 41–38 ka cal. BP, which may correspond to an overall increase in population densities and group sizes throughout western and central Europe (Davies, 2007; Hublin, 2013, 2015). The rise in population would have resulted in more frequent social interactions within and between different areas, encouraging the establishment and maintenance of regional and group identities. The increase in the occurrence of personal ornaments throughout the Aurignacian suggests that these materials were used to help mediate intergroup relationships (Kuhn and Stiner, 2001; White, 1993). Personal ornaments can operate as a medium for establishing group cohesion and identity, while simultaneously reaffirming exclusivity from other groups or individuals (Kuhn and Stiner, 2007a, b). When bearing particular stylistic features and worn in specific arrangements, personal ornaments can contain coded information meant to expedite the identification of an individual within a larger cultural framework (Vanhaeren and d'Errico, 2006). Previous studies focusing on large-scale regional patterns of Aurignacian personal ornaments have proposed that characteristic bead typologies may indicate unique ethnolinguistic groups or cultural identities.

In a study conducted by Vanhaeren and d'Errico (2006), the authors identified three main cultural clusters based on bead types found throughout Europe and the Levant. Of these, the sites in the Swabian Jura formed their own distinct group, suggesting a cultural tradition unique to this population and region. They furthermore argued that personal ornaments can operate as mechanisms to study changes in population structures, exchange networks, language, and belief systems. Alongside personal ornaments, we believe that studying large-scale patterns of pigment use can also be highly informative regarding cultural practices in both functional and symbolic realms. Although Kuhn and Stiner (2007b) suggested that beads and pigments operated at different levels of personal ornamentation and reflect different types of interaction between individuals and groups, the basic principal is the same. Both artifact types require a certain amount of investment. The costs associated with pigment procurement and creation can indeed be quite high, and more research has shown that pigments were being collected and transported great distances, perhaps based on their visual and tactile qualities (Dayet et al., 2016; Brooks et al., 2018; Velliky, 2019). Ethnographic studies have discussed the relationship between the value of certain ocher materials and the distances they traveled, with certain distant sources being particularly sought after (Bleek and Lloyd, 1911; Bates, 1930; Rudner, 1982). Although they argue that pigment as a body paint cannot be directly transferred between individuals, pigment nodules or prepared powder certainly can.

Pigments, unlike personal ornaments, can operate in a number of mediums both practical and symbolic. Experiments have shown ocher to be useful as a sunscreen (Rifkin et al., 2015), hafting agent (Wadley, 2005; Hodgskiss, 2006; Zipkin et al., 2014), nutritional supplement (Abrahams, 2010; Macintyre and Dobson, 2017), astringent (Velo, 1984), and insect repellent (Rifkin, 2015). Although pigments, from a perspective of personal ornamentation, are limited to body painting, their acquisition, processing, and diversity of applications are more wide-ranging than traditional body ornaments. Although beads can perhaps reveal more information on aspects specific to social signaling (Kuhn, 2014), in-depth studies of pigment assemblages have the potential to inform on several levels of cultural and symbolic systems. These systems include, but are not limited to, collection and acquisition strategies and the behavioral mechanisms behind these, diachronic and synchronic changes in cultural preferences and the role of symbolic and functional impacts on these, local and long-distance trade and social exchange, transgenerational knowledge sharing, technological and functional properties behind the use of pigment, and the interplay of these aspects over time.

Currently, the majority of research concerning pigment use on personal ornaments from early (>35 ka) contexts is restricted to the African continent (Bouzouggar et al., 2007; d'Errico et al., 2005; Henshilwood et al., 2004) or the Levant (Vanhaeren et al., 2006; Mayer et al., 2009), although some European Aurignacian sites mention the presence of red staining or colorant on personal ornaments (Otte, 1979; White, 1995; Hublin et al., 2020). Often (except for White, 1995), the reported beads are made of marine, freshwater, or terrestrial shells. As of yet, there are no reported shell beads from the Aurignacian layers at Hohle Fels, or from the early or recent excavations at Vogelherd (although some are reported from later layers of Hohle Fels; e.g., Kölbl and Conard, 2003; Rähle, 1994). Aside from obvious visual and typological differences, the technological aspects of ivory bead production are more complex and require a greater time investment than the manufacture of shell beads (although this does not account for bead provenance, trade, or movement of materials). Shell beads are often kept in their original form, with a perforation, notch, or use-wear to suggest their status as a personal ornament (d'Errico et al., 2005; Vanhaeren et al., 2019). One exception to this is ostrich eggshell beads which appear in the African MSA (McBrearty and Brooks, 2000; Miller and Willoughby, 2014). Ocher residues are reported on ostrich eggshell beads from Holocene contexts in Africa (Dayet et al., 2017) and from ca. 30 ka in China (Pitarch Martí et al., 2017). Our study offers evidence for a similar type of behavior in the Aurignacian for ivory personal ornaments.

Through the presence of anthropogenic ocher on the ivory personal ornaments, as well as ocher pieces from the earliest Aurignacian levels at Hohle Fels, we infer that it is likely that these behaviors were in place at the onset of the arrival of anatomically modern humans into the region. Previous research on the provenance of archaeological ochers from Hohle Fels, Geißenklösterle, and Vogelherd shows that the inhabitants of these caves shared access to several local (ca. <40 km) ocher outcrops or were sharing ocher materials from these local outcrops after collection during the Aurignacian (Velliky, 2019). Regarding Hohle Fels and Vogelherd, we now have evidence that the inhabitants of these two cave sites shared behavioral aspects in ocher collection and use and bead production, among other symbolic artifacts (Dutkiewicz et al., 2018).

5. Conclusions

The results presented here offer one additional aspect to the list of ocher behaviors observed throughout the Upper Paleolithic of Europe: the use of hematite-rich materials to polish ivory personal ornaments. Based on the current archaeological evidence, it is likely that other Aurignacian groups used hematite-rich ochers to polish personal ornaments in Western Europe and the Levant.

For example, Hublin et al. (2020) reported some personal ornaments from Bacho Kiro bearing visible 'red staining,' although they did not confirm that it is indeed hematite or iron oxide (see also Otte, 1979; White, 1995, 1997). A study by Tejero et al. (2020) revealed regional similarities in beads crafted from faunal elements, specifically red deer teeth, with the European and Levantine Aurignacian, and also noted the use of iron oxides to assist in bead production. Although identifying the direct uses of ocher and pigments in these contexts is more ephemeral, our study reveals that one behavioral practice is likely shared among Aurignacian groups in both of these regions.

From the Swabian Jura, the presence of ocher artifacts and ocher residues on numerous ivory beads spanning a minimum of seven millennia from two archaeological sites suggests that ocher pigments were not used in isolation, but rather formed a shared cultural practice that spanned both time and space. The use of ocher and pigments is likely more widespread than is currently known, and increased research on Upper Paleolithic pigments can reveal new aspects of this cultural practice that has been part of human behaviors since ca. 280 ka (Barham, 2002; Watts et al., 2016). As we exemplify in this study, increased intensive analyses of past assemblages may bring to light previously unnoticed ocher residues on personal ornaments and other artifact types. We therefore hope that our study encourages further research into the complexities surrounding pigment use, personal ornaments, and ancient human behaviors during the early Paleolithic of Europe.

Declaration of competing interest

The authors report no conflict of interest.

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Author contributions

E.C.V., P.S., and S.W. conceived the study. S.W. and E.C.V. performed macroscopic analyses on the beads. Scanning electron microscopy and energy dispersive X-ray spectrometry analyses were conducted by E.C.V. and P.S.; Raman spectroscopy was performed by L.B.-G. who, along with E.C.V. and P.S., contributed to data collection and interpretation. X-ray diffraction (XRD) of the sediment samples was conducted by E.C.V., with P.S. providing input and data interpretation for XRD data. S.W. and N.J.C. provided materials and resources. E.C.V. wrote the article, with input from all coauthors.

Supplementary Online Material

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