



# Burning, dumping, and site use during the Middle and Upper Palaeolithic at Hohle Fels Cave, SW Germany

Diana Marcazzan<sup>1</sup> · Christopher E. Miller<sup>1,2,3</sup> · Nicholas J. Conard<sup>2,4</sup>

Received: 24 May 2022 / Accepted: 8 August 2022 / Published online: 23 August 2022  
© The Author(s) 2022

## Abstract

Dumped deposits are a valuable source of information for inferring past behaviour. They provide insights into site maintenance, social organization and settlement dynamics. Hohle Fels Cave in SW Germany offers a unique opportunity to investigate the importance of dumping and site maintenance during the Middle and Upper Palaeolithic of the Swabian Jura. In this paper, we analyse anthropogenic deposits at Hohle Fels employing micromorphology and fabric analysis in order to reconstruct their formation and understand the human behaviours behind their accumulation. Our study indicates that dumping residues from combustion features in the interior of Hohle Fels Cave has a long history extending back to Neanderthal occupation at the site during the Middle Palaeolithic. Despite some reworking via down-slope movement, most of the features demonstrate that the site's inhabitants dumped burnt material, which was previously the fuel for domestic hearths, in specific locations within the cave. The intentionality of the action and the characteristics of the features provide important information for reconstructing the mode and spatial organization of occupations at the site. The combustion features from the Middle Palaeolithic allow us to reassess the hypothesis that Neanderthals' use of the site was less intense and documented a lesser degree of spatial patterning than subsequent Upper Palaeolithic occupations. This research also provides insight for examining the regional variability of pyrotechnology and site maintenance during the Middle and Upper Palaeolithic.

**Keywords** Dumped deposit · Micromorphology · Micro-XRF · Fabric analysis · Upper and Middle Palaeolithic

## Introduction

High-resolution, sediment-based studies have become increasingly significant over the past decade for the interpretation of the structure and spatial organization of archaeological sites (Goldberg and Whitbread 1993; Matthews et al. 1997; Courty 2001; Meignen et al. 2007; Goldberg et al. 2009; Shillito et al. 2011; Wadley et al. 2011; Miller et al.

2013; Villagran 2014; Karkanas et al. 2015; Brönnimann et al. 2020; Haaland et al. 2021). These studies have shown that human actions leave behind traces in the form of features and anthropogenic deposits that can be investigated using a range of microscopic and molecular techniques—the so-called microcontextual approach (Goldberg and Berna 2010)—that can provide valuable information on how people conceptualized and utilized domestic space in the past (Goldberg et al. 2009; Shillito et al. 2011; Miller et al. 2013; Banerjea et al. 2015; Karkanas et al. 2015; Haaland et al. 2021).

Particularly in Palaeolithic contexts, many micromorphological and microcontextual studies of anthropogenic deposits have focused on combustion features and in particular hearths (Macphail and Goldberg 2000; Karkanas 2002; Vallverdú et al. 2005; Berna and Goldberg 2008; Aldeias et al. 2012; Leierer et al. 2020) where hearths are defined as “the intact remnant of a fire that preserves most of the original structure or compositional element” (Dibble et al. 2009, p187). However, a hearth only represents one step within the potential life history of a combustion feature (Bentsen 2014).

✉ Diana Marcazzan  
diana.marcazzan@uni-tuebingen.de

<sup>1</sup> Institute for Archaeological Sciences, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany

<sup>2</sup> Senckenberg Centre for Human Evolution and Palaeoenvironment, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany

<sup>3</sup> SFF Centre for Early Sapiens Behaviour (SapienCE), University of Bergen, Post Box 7805, 5020 Bergen, Norway

<sup>4</sup> Department of Early Prehistory and Quaternary Ecology, University of Tübingen, Schloß Hohentübingen, Burgsteige 11, 72070 Tübingen, Germany

Once a fire has burnt out, people can abandon the hearth or reuse it; they can also clean it by sweeping or rake-out or remove the ashes and combustion residues completely and dispose of them elsewhere within or outside of the occupation area, i.e. dumping. Although sweeping and dumping ultimately disturb the original structure of the hearth, these actions are still important aspects of the range of activities associated with fire-related behaviours (Miller et al. 2010) and thus the life history of a feature. Additionally, sweeping and dumping of hearths can be thought of as types of maintenance activities that provide insights into a site's spatial organization, occupational intensity and settlement dynamics (Goldberg et al. 2009; Miller et al. 2013; Haaland et al. 2021). Thus, it is essential to be able to distinguish between a combustion feature that represents an intact hearth versus a combustion feature that been swept or dumped (Miller et al. 2010; Mallol et al. 2017).

Dumping is one of the main processes of discard recorded in the archaeological record (Karkanas and Goldberg 2018), and the resulting deposits are often described in the literature as trash/discard deposits, domestic waste or middens, when the process of dumping is regularly repeated (Shillito 2015). These types of deposits form when humans remove waste material from the primary occupation area, such as the remains of fuel from a hearth, and dispose of it elsewhere (Miller et al. 2010; Brönimann et al. 2020). For this reason, deposits associated with dumping are usually found on the periphery of the occupation area (Binford 1978).

Understanding the role of discard and waste disposal in the accumulation of archaeological deposits is a central aspect of both Binford's models of hearth-centred occupation (Binford 1978) and also Behavioral Archaeology's emphasis on site formation processes (Schiffer 1972). An artefact can be temporarily or irretrievably removed from an activity area but still remain within the site. Humans can deposit artefacts or drop them unnoticed (*de facto* refuse), collect and dispose of them somewhere else (primary refuse) or relocate them several times (secondary refuse) (Schiffer 1972). This close connection between everyday activities, the objects themselves and their final location makes waste repositories critical for understanding the internal dynamics of human groups. Deposits formed through dumping, therefore, can be thought of as either primary or secondary refuse, depending on their formation history.

Ethnoarchaeological studies of hunter-gatherer groups (Marshall 1976; Yellen 1977; Murray 1980; Binford 1996) report a relationship between how groups structure and maintain their campsites and how they move about on the landscape. For example, ethnographic studies of sedentary and semi-sedentary groups (Murray 1980) showed how the designated areas for waste material are in a distinct location far from the living space. Further, Yellen (1977) observed that, when the occupation lasts for shorter

periods, few formal divisions occur between subsistence and manufacturing processing areas. On the other hand, when the occupation lengthened over time, fuel remains, and other refuse were disposed of in designated area. In particular, Brooks and Yellen observed that in !Kung camps (Brooks and Yellen 1987), occupants left waste material at its production location during short occupations. In contrast, however, fuel remains and refuse were dumped outside of the camp during longer-term occupation. These observations have led some geoarchaeologists to argue that increased evidence for structuring of waste at hunter-gatherer archaeological sites likely reflects an increase in site occupational intensity and potentially also an increase in the length of occupation (Goldberg et al. 2009; Miller et al. 2013; Karkanas et al. 2015; Haaland et al. 2021).

Anthropogenic deposits and features interpreted as having formed through dumping activities have been described from a number of well-known Pleistocene hunter-gatherer sites, including Kebara Cave (Meignen et al. 2007), Üçağızlı Cave (Kuhn et al. 2009; Baykara et al. 2015), Hohle Fels (Schiegl et al. 2003), Lakonis I (Starkovich et al. 2020), Sibudu Cave (Goldberg et al. 2009), Diepkloof (Miller et al. 2013) and Bushman Rockshelter (Porráz et al. 2015). In 2003, Schiegl and colleagues (Schiegl et al. 2003) applied micromorphology to investigate Palaeolithic dumped deposits, focusing their study on the Gravettian-aged "burnt bone layer" IIcf at Hohle Fels, with the aim of distinguishing between intact hearths and dumped deposits. Layer IIcf appeared as a discrete, dark-coloured stratigraphic unit that was laterally extensive across > 12m<sup>2</sup> of the site and has a thickness of 3–10 cm. The layer is rich in archaeological material, including numerous lithic artefacts as well as an engraved stone resembling a phallus that was also likely used as a retoucher (Conard and Kieselbach 2006). The sediment of this deposit is largely composed of sand-sized fragments of dark-coloured bone, presumably burnt.

This enigmatic layer was initially investigated by Waibel (2001) who suggested that the burnt material was redeposited and derived from a large hearth located deeper inside the cave; however, the presence of such a hearth area was never reported and is unclear (Miller 2015). Waibel implicitly assumed that the redeposition of this material was a result of natural colluvial processes acting along the steep slope of the deposits within Hohle Fels. Schiegl et al.'s (2003) micromorphological analysis of IIcf confirmed that the layer is largely composed of charred and unburnt bone fragments and that ashes derived from the burning of plants are largely absent. Their analysis revealed that, microscopically, the deposit has a high porosity and no evidence of compaction, implying little to no post-depositional trampling. Additionally, the observation that charred and unburnt bone fragments are found directly adjacent to one

another implied that the bones were burnt elsewhere and subsequently redeposited.

Contrary to Waibel's interpretation, however, Schiegl et al. argued that the redeposition was likely related to anthropogenic activity. They attributed the formation of the deposit to intentional dumping from several hearths (Schiegl et al. 2003) and argued that the likely location of these hearths, and the associated occupation, was closer to the entrance and not deep in the back of the cave (Schiegl et al. 2003). Following the Schiegl et al. (2003) study, further combustion features, albeit much more laterally constrained, were uncovered through excavation at Hohle Fels. In his study of site formation processes at Hohle Fels and Geißenklösterle, Miller (2015) analysed five additional features (1 from GH 8, 1 and 6 from GH 7 and 1 from GH 6a) from Aurignacian-aged deposits. He noted that despite their smaller size, their micromorphological characteristics were very similar to IIcf. These features exhibited an adjacent occurrence of combusted materials with varying degrees of burning, no burnt substrate and high porosity. Based on the results of experiments aimed at replicating sweeping, dumping and trampling of combustion residues (Miller et al. 2010), Miller (2015) argued that like IIcf, these features also likely represent intentionally dumped deposits. These investigations led to the awareness that the practice of dumping at Hohle Fels was part of a wider cultural and behavioural system that regulated the hygiene and maintenance of the site (Schiegl et al. 2003; Miller 2015). Miller noted that dumped combustion features are only found within the Upper Palaeolithic occupations at Hohle Fels and are thus linked with more intense phases of occupation (Conard et al. 2006; Conard 2011). Thus, he argued that the repetitive dumping of combustion residues and waste within the cave may reflect periods of longer-term occupation of the site (Miller 2015).

Refuse dumps can take on a wide range of shapes and sizes which is dependent on the pre-existing morphology of the substrate and on the subsequent human activities and natural processes that impact their formation (Karkanas and Goldberg 2018). Additionally, the field and microscopic characteristics of anthropogenically dumped deposits often replicate those formed through down-slope, rapid movements (Miller et al. 2010). These mass movements can regularly occur within archaeological sites (Karkanas and Goldberg 2018), making it important to distinguish between deposits formed through colluviation and those formed through anthropogenic dumping. Downslope deposits usually preserve a wide range of characteristics that sometimes can be ascribed to a specific process. For example, debris flows are usually poorly sorted, the coarse particles are encased in a silty clay matrix, and the deposit lacks regular microscopic lamination, or as in the case of rock and debris falls, they show significantly high porosity (Karkanas and Goldberg 2018). For a better understanding

of mass wasting deposits and how they impact the archaeological record, researchers have regularly employed clast orientation studies, or fabric analysis, both on experimental and archaeological deposits (Bertran and Texier 1995, 1999; Bertran et al. 1997; Lenoble and Bertran 2004; Lenoble et al. 2008). For example, fabric analysis on natural clasts within a debris flow reveals that the long axes of clasts are often oriented parallel to the slope direction (Bertran et al. 1997; Lenoble and Bertran 2004), to the extent that the clast in these deposits show weak or strong imbrication, as is the case in grain flows (Bertran and Texier 1999). Therefore, by recording the orientation (trend and bearing) of elongated artefacts and natural clasts during excavation, researchers can use fabric analysis to reconstruct potential modes of deposition (Benito-Calvo et al. 2009; Sánchez-Romero et al. 2016; McPherron 2018; Giusti et al. 2019; Li et al. 2021) and also investigate the impacts that previous substrate morphologies have on the clast orientation (Li et al. 2021). Despite the increasing regularity with which fabric analysis has been employed for the reconstruction of site formation processes, little work to date has focused on the analysis of fabrics internal to combustion features.

## Aim of the study

Since the publication of the original studies of combustion features from Hohle Fels by Miller, Schiegl and colleagues (Schiegl et al. 2003; Miller et al. 2010; Miller 2015), continuing excavations at Hohle Fels have uncovered a total of 36 combustion features, 16 of which have been sampled for micromorphological analysis. Furthermore, recent excavations in 2020 and 2021 in Middle Palaeolithic deposits at the site have uncovered the first evidence for combustion features associated with Neanderthal occupation (Conard et al. 2021). With a larger sample size of combustion features, it is now possible to examine in more detail whether the features at Hohle Fels solely represent intentional dumping of waste or if they record evidence of other activities related to fire use or site maintenance. Thus, in this paper, we aim to identify if there is any diachronic variation in the composition, fabric and microstratigraphy of the combustion features found at Hohle Fels. If compositional variation is present, does it reflect variation in fuel selection strategies as, for example, documented at the Palaeolithic site of Fumane, Italy (Marcazzan et al. 2022)? Or, do we see consistent evidence for extensive burning of bone throughout the Palaeolithic? Are there any variations in fabric and microstratigraphy that would suggest that other anthropogenic processes besides dumping have impacted the formation of these features? Are all combustion features formed through intentional dumping, as suggested by Schiegl et al. (2003) and Miller (2015), or do some of them represent intact hearths?



Furthermore, the broader temporal and spatial coverage of the current set of samples allows us to investigate the role, if any, slope processes played in the formation history of these features. Do all of the features and their microscopic characteristics represent intentional dumping, or have slope processes impacted these features following their deposition?

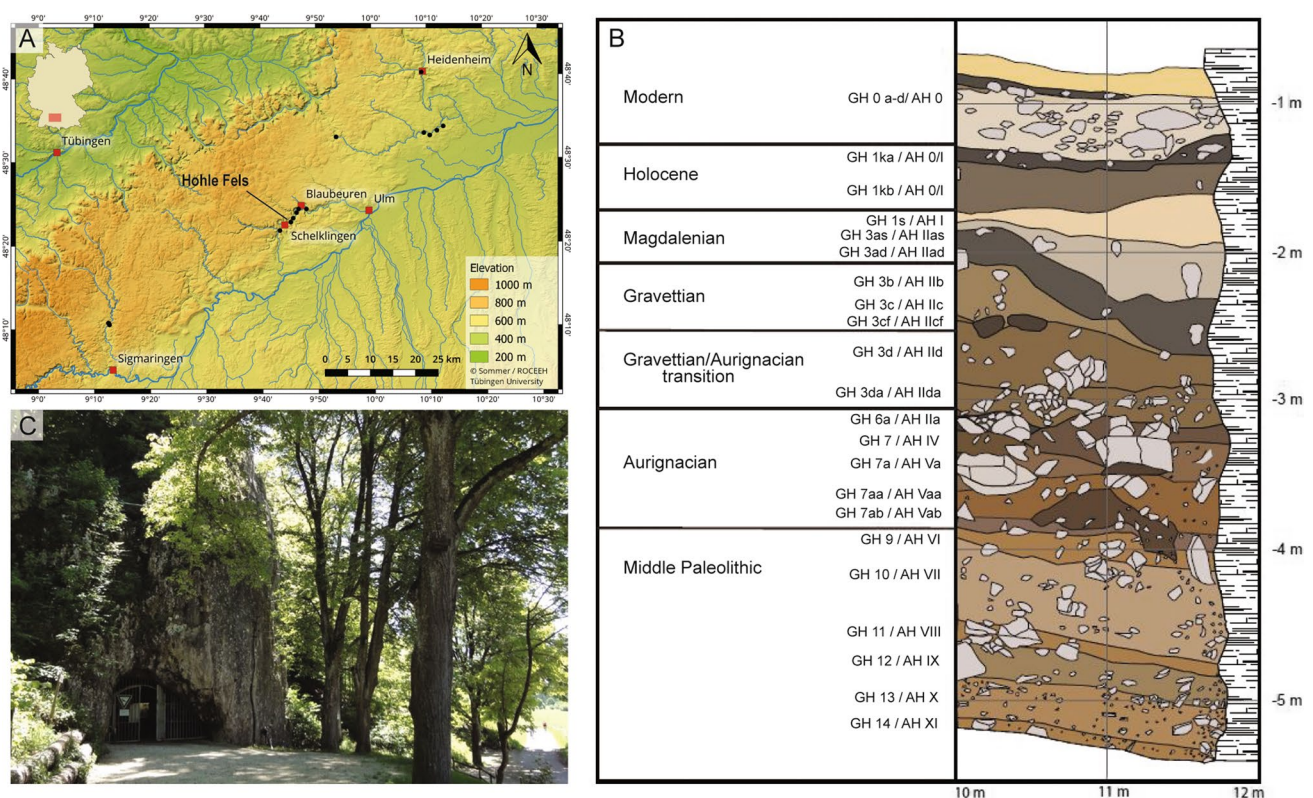
Ultimately, by addressing these questions and constructing a more detailed formation history of combustion features at Hohle Fels, we aim to expand our understanding of the variation of activities related to occupation and use of fire at the site, both by modern humans and Neanderthals. As such, this study contributes also to our broader understanding of Palaeolithic settlement dynamics within the Swabian Jura.

## Site and the archaeological context

Hohle Fels (Fig. 1) is situated at 534 m above sea level (asl) in the valley of the Ach River, a tributary of the Danube, within upper Jurassic (Malm) limestone bedrock (Goldberg et al. 2003). It lies in the eastern portion of the Swabian Jura, a plateau that exhibits numerous geomorphic features typical

of a karstic landscape (Geyer and Gwinner 1991; Goldberg et al. 2003; Schiegl et al. 2003; Miller 2015).

Hohle Fels is one of several important Palaeolithic cave sites in the Ach Valley, in addition to Geißenklösterle (Conard et al. 2019), Sirgenstein (Münzel and Conard 2004), Brillenhöhle (Riek 1973) and Große Grotte (Wagner 1979). Together with the Palaeolithic cave sites in the Lone Valley, the Ach Valley and its caves have recently been declared UNESCO world heritage sites due to their exceptional preservation of ice age mobiliary art and their significance for our understanding of the transition from Neanderthals to modern humans in Europe. Hohle Fels is one of the largest caves in the region with evidence of Pleistocene human occupation, having an interior that extends across ca. 500 m<sup>2</sup> (Miller 2015; Velliky et al. 2018). The large size of the cave and its relative accessibility attracted early ice-age researchers, such as Oskar Fraas and Theodor Hartmann (Fraas 1872), who conducted some of the first palaeontological and archaeological investigations in southern Germany at the site (Fraas 1872; Riek 1934; Hahn et al. 1978). In 1973 Joachim Hahn and colleagues recommenced research in the Ach valley, initiating archaeological systematic excavations at Geißenklösterle and Hohle Fels following the French style



**Fig. 1** Site location and stratigraphic sequence. **A** Map of the Swabian Jura of southwestern Germany with the location of Hohle Fels. Map courtesy of C. Sommer, University of Tübingen (<https://doi.org/10.5281/zenodo.34,603.01>). **B** Stratigraphic profile highlighting

the cultural periods in correlation with the geological horizons (GH) and the archaeological horizons (AH) (by A. Janas). **C** View of Hohle Fels entrance (D. Marcazzan)

(Hahn 1977). After Hahn's untimely death in 1997, Nicholas Conard and Hans-Peter Uerpmann of the University of Tübingen carried on the excavations (Conard and Uerpmann 2000), which continue to this day under the direction of Nicholas Conard (University of Tübingen).

Excavations at Hohle Fels have exposed a long sequence (Fig. 1) of mostly Pleistocene-aged deposits that contain evidence of Middle and Upper Palaeolithic occupations. The definition of strata at Hohle Fels follows the typical Tübingen approach to stratigraphic designations, with discrete stratigraphic units called *Geologische Horizonte* (GH) and *Archäologische Horizonte* (AH). GHs represent units that are defined largely on lithological characteristics observable in the field, such as grain-size, colour, fabric, inclusions and also the nature of the upper and lower bounding contacts (Goldberg et al. 2003; Mallol and Mentzer 2015). AHs are stratigraphic units that are defined on the basis of archaeological assemblages. Within this system, GHs are given Arabic numerals that ascend with increasing depth (GH 1, GH 2, GH 3, etc.). AHs follow the same system but are given Roman numerals (AH I, AH II, AH III, etc.). Subdivision of a GH or AH, often occurring during post-excavation analysis, is possible and the resulting sub-units are given lower-case suffixes (e.g. GH 1a, GH 1b and AH Ia and AH Ib). Following this system, it is then possible that a single GH may contain more than one AH if, for example, two discrete concentrations of artefacts are found within a GH that appears lithologically uniform. Similarly, it is possible to have a GH that has no AH designation if the GH is archaeologically "sterile", i.e. there was no cultural material uncovered during excavation. All excavated archaeological material from Hohle Fels is assigned to both a GH and a corresponding AH, and thus these designations represent not only an essential component of the stratigraphy of the site, but also a key unit of analysis for all finds and samples. A third type of stratigraphic unit in the excavation system at Hohle Fels is the *Befund* or feature. Features are defined as units that are lithologically distinct from the surrounding deposits but that are spatially constrained. Although in practice, at Hohle Fels, features are usually implied to be anthropogenic in nature and origin, this does not necessarily need to be the case. All features are excavated separately and thus represent a distinct stratigraphic and analytical unit. However, all features are assigned to a specific GH/AH and given a name, such as Bef. 6 GH 7, which indicates the sixth feature designated within GH 7.

### Previous geoarchaeological studies

Hohle Fels has a long history of geoarchaeological analysis (Goldberg et al. 2003; Schiegl et al. 2003; Miller 2015; Barbieri et al. 2018, 2021), which saw the application of a number of different analytical techniques. In addition to the

previously mentioned study of combustion features (Schiegl et al. 2003; Miller 2015), Goldberg and Miller focused on the depositional and post-depositional processes acting at the site. They analysed thin sections from the Middle Palaeolithic to the Magdalenian layers, revealing greater sedimentary heterogeneity than what appeared during the excavation. Overall, the main components consist of calcareous and phosphatic clay, éboulis, lithic fragments, bone, charcoal and organic material. Their abundance and consistency characterize the differences between the various GHs.

Goldberg et al. (2003) and Miller (2015) group the GHs (and their corresponding AHs) into lithostratigraphic units, using capital roman letters. These lithostratigraphic units broadly correspond with the cultural designations of the stratigraphic section. The Middle Palaeolithic, unit E, covers from GH 15 to GH 8. In general, it consists of phosphatized calcareous clay that was probably washed downslope from the back of the cave (Miller 2015), especially for the lowest layers. Further indications that water action is the main agent in the layer formation are also the common clay intercalation and infillings. We have found few archaeological finds in the more recent Middle Palaeolithic levels. This trend changes with the transition from unit E and D (GH8 and GH7). In fact, the Aurignacian sees an increase in the density of the archaeological finds (Goldberg et al. 2003; Conard et al. 2006; Miller 2015). The transition also witnesses an abrupt break with the sedimentary trend, going from highly phosphatized clay (GH 8) to highly calcareous clays (GH 7) (Miller 2015). Water still played a consistent role in GH 8 with the presence of clay coatings and intercalation, which are absent in GH 7. On the other hand, GH 7 preserves platy structures typical of colder conditions (Miller 2015), such as rounded aggregates and other freeze-thaw indicators. However, the Aurignacian, unit D (from GH 7 to 3d), within the following layers, shows different characteristics which Goldberg et al. (2003) and Miller (2015) interpreted as reflecting a relatively warmer period and with higher moisture, where the biological activity promoted extreme phosphatization of the matrix (Goldberg et al. 2003; Miller 2015). In contrast, the Gravettian layers, unit C, appear more homogeneous than unit D (Miller 2015). Their composition is mainly calcareous (Miller 2015), and they show characteristics typical of cold conditions. Cryoturbation likely accounts for the presence of rounded aggregates and platy ice-lensing microstructure (Goldberg et al. 2003; Miller 2015). The upper part of the sequence includes units B and A. Unit B marks a break from the previous units. The contact appears sharp and distinct (Miller 2015) suggesting a possible erosional event between the Gravettian and the Magdalenian. The following unit A comprises the Magdalenian and the Holocene layers (Goldberg et al. 2003). The Magdalenian layer preserves phosphatic grains within a calcareous matrix (Miller 2015), pointing to a colder environment.

The identification of the units and their characteristics provided useful data to build a depositional model of the site, which includes a range of processes. Work by Goldberg et al. (2003) and Miller (2015) indicates that limestone blocks, due to the action of freeze–thaw, fall from the roof and wall of the cave. The physical and chemical alteration of most of these suggested that they were transported downwards after falling (Miller 2015). For the fine fraction, they proposed a highly variable depositional history (Miller 2015). In some layers, the clay is derived from the karstic system, through water percolation. In other layers, the clay occurs as aggregates with quartz-silt inclusions. Their presence in the deposits involves the large chimney at the back of the cave through which sediment entered. Once inside the cavity, it began to move down the slope towards the entrance because of cryoturbation.

However, if this model explains why the layers formed, it does not explain why we have an erosional contact in unit B. This observation led to the work of Barbieri and colleagues. Across the Pleistocene and Holocene, the land formation model (Barbieri et al. 2018, 2021) in the Ach valley sees phases of soil formation, hillslope denudation, river valley incision and floodplain aggradation. The alternation of these phases, especially those related to the Last Glacial Maximum, contributed to the formation of the archaeological deposits in the valley floor but also resulted in the erosion of the hillslopes and also some of the deposits contained within the cave.

## Materials and methods

Since the stratigraphy and sample set of Hohle Fels have such a broad temporal and spatial coverage, the objective of this study is a diachronic analysis of combustion features from the Middle to Upper Palaeolithic in order to reconstruct their formation history. Here we employ a range of geoarchaeological techniques, including micromorphology, micro-X-ray fluorescence and fabric analysis of geological deposits and features. A total of 37 features have been defined in the Palaeolithic deposits at Hohle Fels, 17 of which have been sampled as blocks for micromorphological analysis (Table 1). Each feature was described in detail in the field, often over several field seasons where the features extended into multiple excavation units. A summary of these descriptions for each feature is provided in Table 1. In addition to field description and sampling, all features were photographed (Fig. 2) and their outer limits recorded with a total station. Most of the features are a square metre to a few square metres in total area, the main exception being IIcf, which is laterally extensive across almost the entire area of excavation. Although IIcf is anthropogenic in origin and likely shares a similar formation history with other features

at the site (Miller 2015), it was not designated as a feature during excavation but rather was given its own GH and AH designation (3cf, IIcf). Several of the more laterally extensive features, including IIcf, were sampled more than once, providing important information on lateral variation of the feature's characteristics.

**Micromorphology** Micromorphological analysis involves the study of undisturbed, oriented blocks of sediment in thin section in order to identify the composition and spatial arrangement of the components within a deposit (Stoops 2021). At Hohle Fels, block samples for micromorphological analysis are regularly collected from all GHs and also from larger features where they are generally removed as monoliths on the horizontal surface during excavation, although occasionally they are taken directly from an exposed profile. The samples are wrapped in plaster-of-Paris bandages, and their exact location is recorded with a total station and then uploaded into a 3D-model (Supplementary information Fig. S1). Thin section production took place in the Micromorphology Laboratory of the Geoarchaeology Working Group, University of Tübingen. After drying in an oven at 40 °C, the samples were impregnated, under vacuum, with a mixture of unpromoted polyester resin, styrene and methyl ethyl ketone peroxide (MEKP) (700/300/5)/L. Once gelled, the samples were again heated to 40 °C, and the hardened blocks were then cut to various formats, mounted on glass and ground and polished to a thickness of 30 µm. We performed the thin section analysis with a Zeiss Axio Imager petrographic microscope under plane-polarized (PPL) and cross-polarized (XPL) light. The description of the thin sections follows Courty et al. (1989), Nicosia and Stoops (2017) and Stoops (2021) employing a systematic descriptive template (Marcazzan and Meinekat 2022). Following description of the samples, we categorized individual microstratigraphic units into different types, following the (micro-)facies concept (Courty 2001; Goldberg et al. 2009). This approach allowed us to interpret a genetic link with the depositional process of the features, facilitating a spatial reconstruction of past human activities (Courty 2001; Goldberg et al. 2009; Villagran et al. 2011; Karkanias et al. 2015; Miller et al. 2013; Haaland et al. 2021).

**X-ray fluorescence spectroscopy (µXRF)** µXRF measures, through X-ray exposure, the relative intensity and energy of the characteristic radiation emitted by a given substance (Mentzer 2017). Its application can provide information about the elemental and mineralogical composition of the sample, mapping of the element's distribution and identification of authigenic minerals (Mentzer 2017). In this study, we used micro-XRF to confirm or rule out oxide staining as

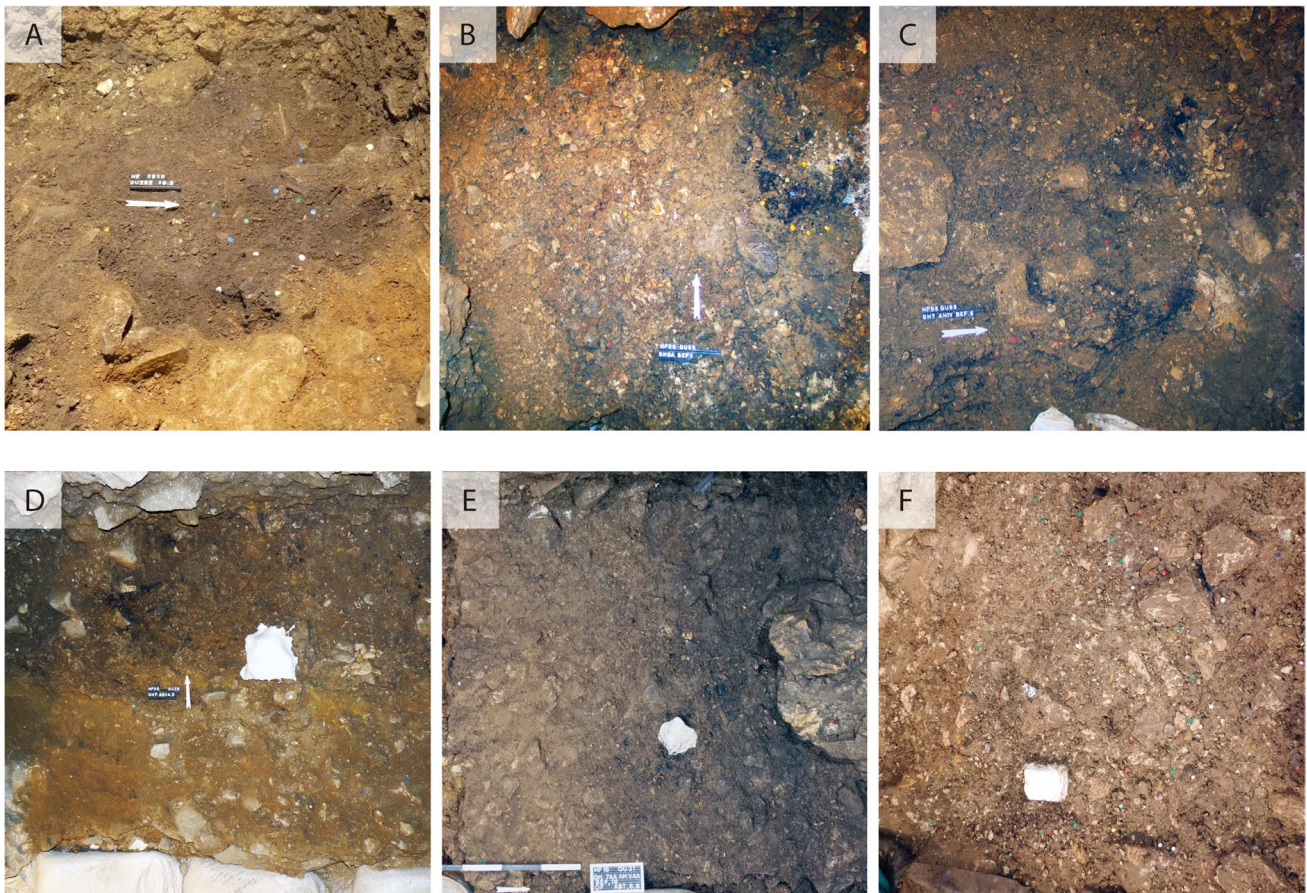
**Table 1** Field description of the combustion features from Hohle Fels and ID of the thin section taken from the feature

GH	BEF	Field description	TS ID
3ad	1	Clayey silt, moist, well malleable and cohesive. Mica is visible, among the calcareous sand. Limestones 40% as in 3ad. Transition to 3b well visible at the lower edge. Many finds such as well-preserved bones, burnt material, painted stone	HF-10-1228A HF-10-1228B
3b	3	The find extends over Qu 45 b and d and is only 6-cm thick in the SE and 2 cm in the NW. Find density is low: one basic form, burnt and unburnt bones. Light clayey silt with good malleability. Finds, like the feature itself, levelled from SE to NW	HF-10-304
3cf	-	Description from profile 8. Ash grey sediment with no cohesiveness. It includes ash with some calcareous sand and some mica but less than in 3c. The black sediment includes mainly burnt bones, and it appears loose but still well cohesive and malleable. Limestones, 40%, have a range size of 3–8 cm, rather sharp edged and preserved a random orientation and distribution	HF-896 HF-572 HF-10 HF-14-1 HF-14-2 HF-14-3
6a	1	Sediment with abundant charcoals has a dark grey to black colour. It is only a few centimetres thick but wide-spread and preserves many lithics and bones Description of the northern part. It shows a black colour with many bones; otherwise, it preserves a very dark grey. The groundmass appears clayey silt with a slightly higher proportion of calcareous sand Clayey silt with little calcareous sand, very cohesive and malleable, low mica content. Limestone content 80–90%, angular, partly fissured and then sharp-edged Black colouring of the sediment comes mainly from the charcoals' content. The sediment is very moist; therefore, it smears strongly and can hardly be deformed. Silty clay with calcareous sand and some mica. Transition to the lying GH 7 is gradual within a few cm It lies clearly between GH 5 and GH 6a, with a clear lateral variability. The dark colour derives from the charcoals and other burnt material. With less burnt material, the colour is rather grey and brown. Boundary to GH 5: Calcareous debris from GH 5 presses on the surface of GH 6a feature 1. Where no GH 5 exists above feature 1, GH 3db lies above. Well-defined transition downwards to GH 6a, with a few cm transition area. The colour is very heterogeneous. The limestone fragments are few or less than 1 cm in size. There are few calcareous sand, clearly visible mica and silty clay. The sediment is very wet; therefore, it smears a lot and can hardly be deformed	HF-88-1476A HF-88-1476B HF-88-1476C HF-30-816A HF-09-762 HF-76-1246B
7	1	Small area of irregular grey-brown to black-brown sediment; the colour is due to charred bones and charcoals; it also contains unburnt bones and limestone fragments that are partially resting directly upon the underlying AH Va Ashy and grey sediment from GH 7 with many pieces of charcoal	HF-69-2722A HF-69-2722B HF-69-2722C HF-69-2722D
7	3	Dark grey-brown sediment. It is not richer in burnt material than AH IV in general Higher percentage of combusted materials such as burnt bones and charcoals. The sediment is loose with micro-granular structure The sediment is richer in clay than GH 7, especially in the west, and wetter with more calcareous sand. Towards the east, the feature tapers off and becomes fuzzy. Limestones: 50%, angular and irregularly embedded, 8–10 cm in size	HF-622A HF-622B HF-15-1269
7	6	Grey-brown sediment with high number of charcoals and charred bones; pit-like form within AH IV. It has abundant lithics, mostly unburnt, bones and ivory fragments Silty clay sediment with high calcareous sand content. It includes charcoals, chert fragments and burnt bones. The burnt material forms black lenses or bands. Limestones range between 3 and 8 cm with random orientation and distribution	HF-2090-B HF-2090-C HF-2090-D HF-2090-E HF-19-2804
7a	7/9	Description of number 7: clayey silt with mica, bones and charcoals. Limestone content is ha 40%, and the fragments are mostly 3–6 cm, not levelled Description of number 9: grey-brown sediment with high content of charcoals and burnt bones. Very rich in finds, many flint and ivory fragments. Most likely belongs together with feature 7	HF-533a HF-533b HF-533c HF-896 a HF-896 b HF-09-1298 HF-1511
7a	10	Slightly clayey silt. More reddish brown than 7a. Limestone's content: <40%, 4–8 cm, and with a random orientation and distribution	HF-08-1185 HF-20-3336
7aa	16	Light clayey silt with calcareous sand and mica. Fine granular structure. Conspicuous concentration of charcoal. Limestone content 60%, highly angular, rounded. Mostly 5–12 cm	HF-15-1198 HF-16-2661
7aa	16+17		HF-16-1699
7aa	11	Compact sediment consisting mainly of bone and some charcoals. The density of find 11 is slightly higher than in the surrounding GH 7aa	HF-09-1341
7aa	12	Characterized by grey-brown colour of the sediment, which is mainly due to bones. There are not intact charcoals. The finds density increase compared to GH 7aa	HF-09-963



**Table 1** (continued)

GH	BEF	Field description	TS ID
8	3	Refers to Qu 57 and 67. The sediment is the same as the surrounding sediment of GH 8. It contains many pieces of bones, charcoals often over 2 cm. The sediment is black-grey to black coloured. The boundaries cover Qu 57, Plan 63 and Qu 67, Plan 67	HF-57–3507
8	14	It includes clearly more charred bones	HF-09–2515
12	1	In Qu 11. It preserves horizontal position of the limestones	HF-18–2086
14	1	It appears with a grey colour, several small clasts. It does not show an orientation of the components. The finds include bones (burnt and unburnt), lithic material and very few charcoals	HF-20–3123



**Fig. 2** Excavation pictures of the features from Hohle Fels. **A** GH 3b feature 3 (limit of the feature visible). **B** GH 6a feature 1. **C** GH 7 feature 6 (limit of the feature visible). **D** GH 7a feature 7=9; **E** GH 7aa feature 16; **F** GH 14 feature 1

the source for the dark colouration of bone fragments within the features.  $\mu$ XRF analysis was conducted on a selection of thin sections, including HF-572, from the Gravettian IIcf, and HF-15–1198, from the Aurignacian GH 7aa feature 16. We conducted the analysis in the Microanalytic Laboratory of the Geoarchaeology Working Group, University of Tübingen using an M4 Tornado (Bruker) micro-XRF. The thin sections were scanned under full vacuum with both detectors, maximum tube voltage of 50 kV and current of 600 microamps with 50 microns spacing, 25 ms dwell per

pixel for the thin sections and with 30 micron spacing for the detail map.

**Fabric analysis** The analysis of the orientation and dip angle of artefacts and clastic, geological elements has been extensively applied in the interpretation of depositional and post-depositional processes acting within geological deposits and at archaeological sites (Benn 1994; Lenoble and Bertran 2004; McPherron 2005, 2018; Benito-Calvo et al. 2009; de la Torre and Benito-Calvo 2013; Lotter et al. 2016; Giusti



et al. 2019; Li et al. 2021). Fabric shape analysis relies upon the relative values of the three eigenvalues (Benn 1994; McPherron 2005, 2018), calculated from the orientation and dip angle data. To effectively determine the disturbance of the archaeological assemblages, Benito-Calvo et al. (2009) proposed that sedimentary fabrics (geogenic clast) should be analysed separately from archaeological fabrics. We applied a similar concept to the analysis of the combustion features, analysing only the archaeological material. At Hohle Fels, the excavators record orientation data on all the anthropogenic material above a certain size limit, depending on the type of find. Every in situ find with a significant long axis is measured with three points using a total station: the middle point of the topside (P1), the highest point of the long axis (P2) and the lowest point of the long axis (P3). Having these data available, we decided to analyse the material (Table 2) belonging to the combustion features separately from the surrounding sediment, in order to assess the extent to which slope movement had impacted their formation. We decided to analyse the material inside the features separately from that outside, since dumping is a purely anthropogenic process if not influenced by slope movement, and so the features should show different results for the dip and the bearing compared with the more geogenic deposits. To perform the fabric analysis, we adapted the script published by McPherron (2018) and Li et al. (2021) in the R statistical software (R Core team 2019). The data required to reproduce the results can be found on GitHub as supplementary information ([https://github.com/dnamrczz/HF\\_features\\_orientation](https://github.com/dnamrczz/HF_features_orientation)).

## Results

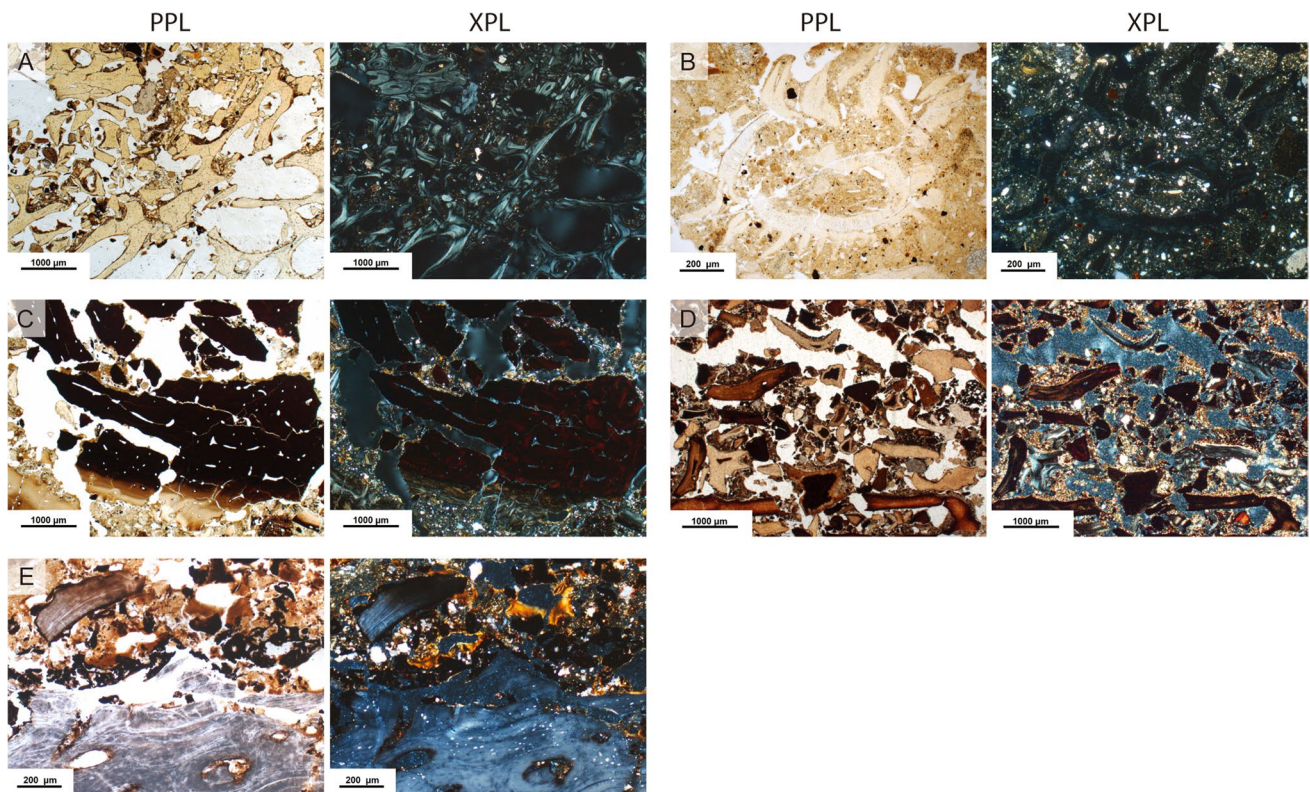
Here we provide results from the micromorphological,  $\mu$ XRF and fabric analyses. Detailed descriptions and flatbed scans of all thin sections are provided in the SI (Table S2 and S3). Below we provide details on the anthropogenic components identified in thin section and also present the types of microstratigraphic units identified from the analysed combustion features.

## Anthropogenic components

**Bones** Bone fragments are numerous within the features and usually range from sand- to gravel-sized. Both cortical and spongy bone is present. The bone fragments exhibit a wide range of colours, implying that they have been subjected to heat, although some bone fragments appear unburnt (Fig. 3A). Colour variation of bones is generally taken to correspond to the degree of heating (Stiner et al. 1995), although there is likely some degree of variation among bones from different species of animals (Nicholson 1993) and among different types of bone with varying fat content (Symes et al. 2008). The addition of samples from previously undescribed combustion features at Hohle Fels confirms the results of earlier micromorphological studies (Schiegl et al. 2003; Miller 2015) that the bones present within the combustion features were exposed to range of temperatures. The bone fragments often exhibit light to medium yellow to dark reddish-black colours in PPL, suggesting that they were exposed to temperatures between 300 and 400 °C (Stiner et al. 1995; Villagran et al. 2017) (Fig. 3C–D). Other bones exhibit pale brown-grey colours in PPL, visible internal fissures and bluish-grey interference colours with an overall milky cast to the birefringence under XPL, implying that they were calcined above 500 °C (Schiegl et al. 2003; Villagran et al. 2017; Mentzer et al. 2017) (Fig. 3E). Both charred and unburnt bones have a high degree of fragmentation (Fig. 3D); however, we observe very few bone fragments that are articulated and accommodating, suggesting that fragmentation is not related to in situ snapping and that trampling likely played a minimal role in the formation of most features (Miller et al. 2010). Most of the bone fragments occur within a monic, chitonic or enaulic cf-related distribution and commonly display a random orientation and distribution. The unburnt bones occasionally show evidence of chemical and biological alteration, such as secondary mineral formation or oxide staining (Villagran et al. 2017). Although the highly fragmented nature of the bone rules out obvious species identification, fish bones (Fig. 3B) are recognizable in several thin sections, and, in some cases, it is possible to identify complete and well-preserved fish vertebrae.

**Table 2** Summary of Hohle Fels elongated artefacts used for orientation analysis

Layer	Feature			Feature ID	Feature		
	Bone (> 3 cm)	Lithic (> 1 cm)	Total		Bone (> 3 cm)	Lithic (> 1 cm)	Total
7_IV	107	43	150	Bef 6	37	37	74
7a_Va	321	262	583	Bef 7	64	68	132
7aa_Vaa	273	201	474	Bef 16	148	138	286
14_XI	40	23	63	Bef 1	28	13	41
Total	741	529	1270		277	256	533



**Fig. 3** Photomicrographs of the anthropogenic components, both in PPL and XPL. **A** In situ crashed fresh bone appearing light pale yellow/colourless in PPL and with a strong low-order interference colour (white, grey, black). **B** Fragmented fish vertebrae showing the typical rounded morphology. **C** and **D** Charred bone fragments having different degrees of fragmentation with colour ranging from light to

medium yellow, dark reddish-brown and finally black (opaque) in PPL and red interference colours with opaque areas in XPL, usually referable to 300–400 °C of burning. **E** Calcine bone fragments displaying a grey colour in PPL and a strong birefringence in XPL with the typical low order of interference from grey to grey with milky cast

**Ivory** Ivory was an important raw material at Hohle Fels, used regularly throughout the Upper Palaeolithic as a raw material for symbolic-representational objects and tools (Conard 2003, 2009; Heckel 2009; Velliky et al. 2021). Using reference material published by Villagran et al. (2017), we were also able to identify fragments of ivory in thin section (Fig. 4A–B) which appears as coarse, angular sand-size blocks. It preserves under PPL bands similar to growth rings and a brown low-order grey of interference colour in XPL (Virág 2012). The fragments appear both burnt and unburnt, and very few are articulated and accommodating, suggesting that they were subjected to little in situ snapping through trampling (Miller et al. 2010). Some fragments appeared stained with manganese oxide, and so this sample was also subjected to  $\mu$ XRF analysis.

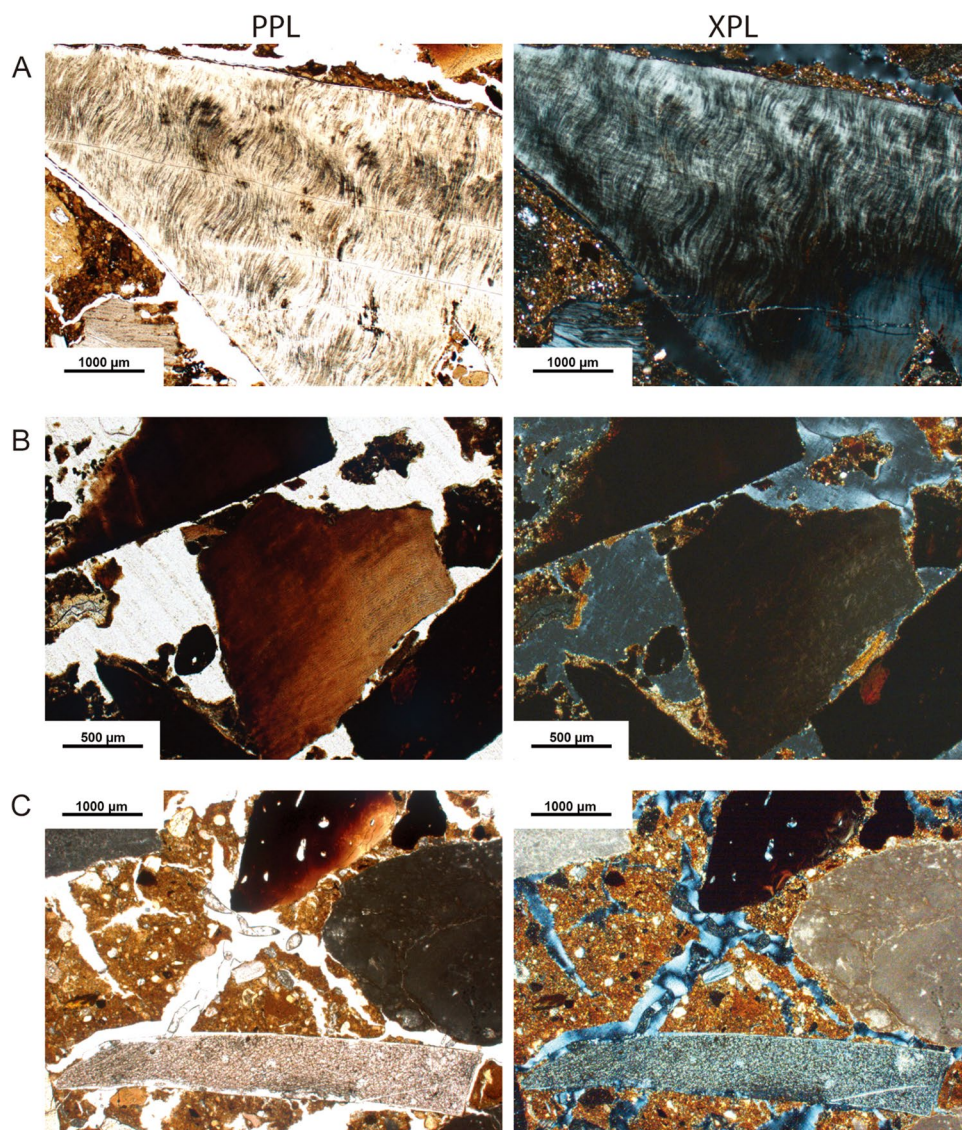
**Fat char** Fat-derived (Ligouis 2017) char is an amorphous organic residue (Mallol et al. 2017) formed through the charring (Villagran et al. 2017) of flesh or animal fat (Goldberg et al. 2009). In thin section, it appears as an opaque, heterogeneous isotropic particle with a high porosity due to the numerous vesicles. We found fat-derived char at Hohle Fels

occurring in two different forms: the classic char occurrence (Fig. 5C–D) preserves the typical vesicular microstructure (Goldberg et al. 2009), with smooth and undulated surfaces and is present as isolated grains usually within the sand-size range; it also appears as char and sediment aggregates (Fig. 5E–F) where the char is generally incorporated into the matrix. In the second occurrence, it preserves a spongy internal microstructure, the size ranges from coarse sand size to fine gravel, but it is not always easy to identify the boundaries with the surrounding matrix.

**Charcoal** Charcoal (Fig. 5A–B) occurs as opaque fragments in PPL and XPL (Canti 2017). Fragments of charcoal are very few and not in every feature. In only one feature (GH 6a Bef 1), charcoal fragments are more frequent than bones and embedded in a groundmass possibly derived from ashes. The fragments usually maintain the typical woody plant structure. When they have in thin section a transverse cut (Canti 2017) (Fig. 5A), their internal structure displays softwood or semi-ring porous hardwoods (Schweingruber 1978), which follow the analysis of Aurignacian charcoal (Riehl et al. 2015) where the main identified species were *Pinus* sp. and in small amounts *Salix*



**Fig. 4** Photomicrographs of the anthropogenic components, both in PPL and XPL. **A** Fragment of fresh ivory exhibiting bands like growth rings in PPL and a brown low-order grey of interference colour in XPL. **B** Charred fragments of ivory partially stained by Mn (see figure X for details on the micro-XRF overview data). It appears dark reddish brown to black (opaque) in PPL with weak interference colours in XPL. **C** Fragments of chipped cryptocrystalline silica



sp. (Riehl et al. 2015). Their size range varies from silt-sized to fine gravel, with both globular and blocky shapes.

**Ash** At Hohle Fels, we do not find much direct evidence for ash derived from the burning of wood or other plants. The ash (Fig. 5A–B) as calcite rhombs are rarely preserved (Canti 2003). Schiegl et al. (2003) noted already this lack of ash in Ilcf, and we also were not able to identify many occurrences of it in the combustion features studied here. Calcareous groundmasses are found in some combustion features, suggesting that if ash had been present, it probably underwent dissolution and recrystallization.

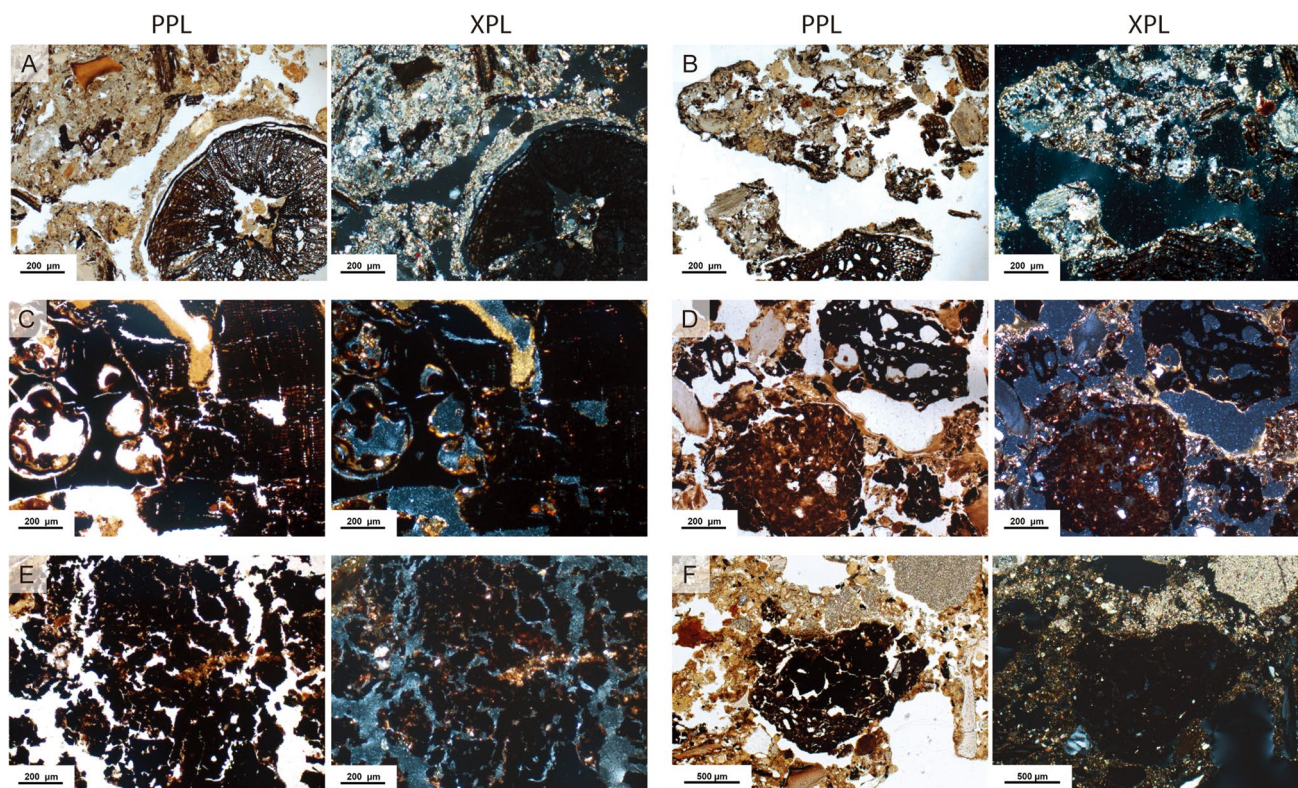
**Chert** In thin section, the chipped cryptocrystalline silica fragments (Fig. 4C) have a very low abundance and preserve a medium to very coarse grain size, a blocky/platy

and angular shape with smooth surfaces. The chert fragments can be attributed to waste from lithic tool production (Angelucci 2017), given also the considerable quantity of artefacts found during the excavation (Bataille and Conard 2018; Taller et al. 2019).

#### Composition of the features and types of microstratigraphic units

The anthropogenic components listed above are generally found within every combustion feature investigated in this study, with the exception of charcoal and ivory. Apart from GH 6a Bef 1, charcoal is relatively rare, and almost every feature is dominated by sand- and gravel-sized fragments of charred bone, together with fat-derived char (Table 3). Thus, there is little compositional variation across the





**Fig. 5** Photomicrographs of the anthropogenic components, both in PPL and XPL. **A** and **B** Fragments of charcoal, appearing opaque both in PPL and XPL, embedded in altered ash. **C** Charcoal fragment and fat-derived char. **D**, **E** and **F** fat-derived char from the burning of flesh and fat. In thin section, it appears black (opaque) in PPL and

XPL. Note the types of char that can be identified. **D** appears with vesicles and small planar voids (classic char). **E** is not easily distinguishable from the surrounding matrix and preserves mainly planar voids (char and sediment aggregate). **F** char preserving a globular shape with mainly planar voids

features, both within the same GH and also diachronically; however, we noted differences in the microstructure and distribution of these components in thin section which allows us to classify the individual microstratigraphic units into three different types. Type 1 (Fig. 6) generally shows a black-dark brown groundmass colour due to the high organic content, although this sometimes appears grey when the groundmass is calcareous. These microstratigraphic units display highly interconnected voids, spongy to vuggy microstructure and frequent to dominant anthropogenic material (usually bones and fat char), which in some cases appear bedded. The components have sizes ranging from medium sand to very coarse sand (fine gravel in a few cases), random distribution and orientation and very little evidence of compaction or in situ snapping. The bones usually show different degrees of burning from low to high temperatures, and in comparison, charred bones are more abundant than non-combusted ones. The components in a few features exhibit rolling pedofeatures such as coatings; however, the main pedofeatures found in most of these microstratigraphic units are thin, unsorted cappings (Fig. 6). Microstratigraphic units classified as

type 2 (Fig. 6) have the same range of anthropogenic components as type 1; however, these components occur as single, isolated inclusions within a geogenic matrix. The groundmass is generally yellow to light brown and consists of silt and clay-sized grains, likely representing phosphatized loess, as identified by Goldberg et al. (2003) and Miller (2015). In contrast to microstratigraphic units categorized as type 1, those in type 2 typically display a blocky, granular or platy microstructure. The anthropogenic components embedded within the geogenic matrix are usually composed of bone and occasionally charcoal, and overall exhibit less evidence of burning compared to the anthropogenic components found in type 1. Similar to type 1, the anthropogenic components in type 2 exhibit a random distribution and orientation. Pedofeatures indicative of rolling (i.e. coatings) are also present and more pronounced in type 2 compared with type 1. A third type (Fig. 7) identifies features with a black groundmass that clearly show lamination and a massive microstructure, with very few voids. The anthropogenic components include bones and charred material, which show a random distribution but a more parallel orientation.

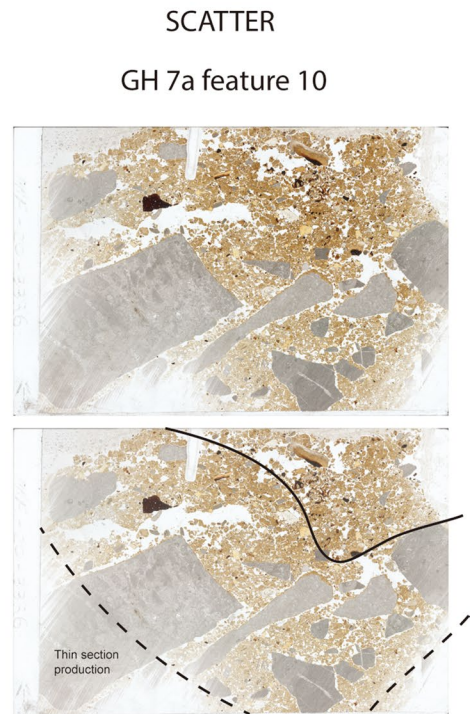
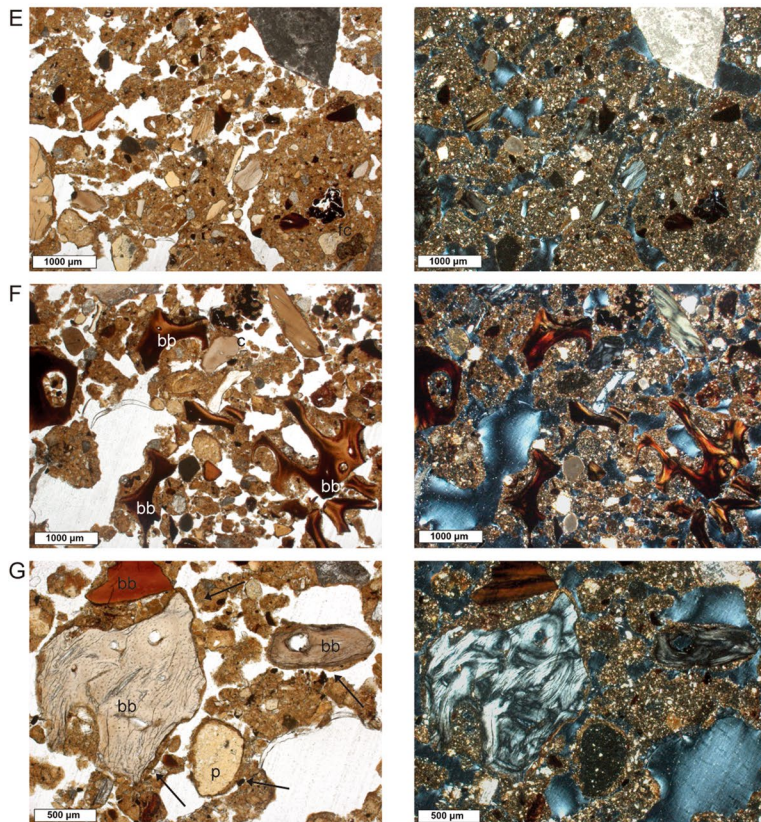
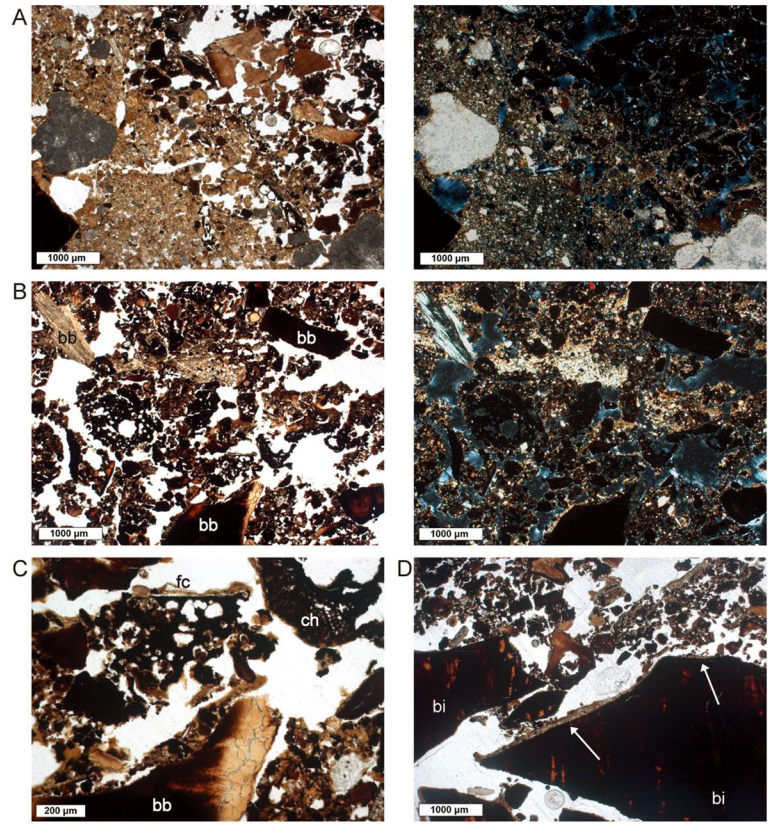
**Table 3** Composition of the primary components, such as unburnt bones, charred bones, fat-derived char, charcoals and ash, from the main anthropogenic microunit. Fabric unit abundance: very few (< 5%) = \*, few (5–15%) = \*\*, common (15–30%) = \*\*\*, frequent (30–50%) = \*\*\*\*, dominant (> 50%) = \*\*\*\*\*

GH	Feature	Thin section ID	Unburnt bones	Charred bones	Fat char	Charcoals	Ash
3ad	1	HF-10-1228A	*	*	*	**	*
		HF-10-1228B	*			*	
3b	3	HF-10-304	*		*		
3cf		HF-896	**	****	***	*	*
		HF-572	*	*****	**		
		HF-10	*	****	**		
		HF-14-1	*	****	**		
		HF-14-2	*	****	**		
		HF-14-3	*	****	**		
6a	1	HF-88-1476A	*	*	*	Rare	
		HF-88-1476B	*	**	*	Rare	
		HF-88-1476C	*	*	*	Rare	
		HF-30-816A	Rare	Rare		Rare	
		HF-76-1246B	*		*	****	***
		HF-09-762	*		*	*	
7	1	HF-69-2722A	*			**	**
		HF-69-2722B	*			**	**
		HF-69-2722C	*			**	**
		HF-69-2722D	*			*	**
7	3	HF-622A	**	*		**	
		HF-622B	*			*	
		HF-15-1269	*	*		**	**
7	6	HF-2090-B	**	***	**	*	
		HF-2090-C	*	****	***	*	
		HF-2090-D	*	***	**	*	
		HF-2090-E	*	**	**	*	
		HF-19-2804	**	***	**	*	
7a	7 = 9	HF-09-1298	*	*	*	*	
		HF-533a	*	****	***		
		HF-533b	*	***	**	*	
		HF-533c	**	***	*	*	
		HF-896a	*	****	***	*	
		HF-896b	*	*****	***	**	
		HF-1511	**	**	**	*	
7a	10	HF-08-1185	*	**	**		
		HF-20-3336	**	**	*		
7aa	16	HF-15-1198	*	****	*****	*	
		HF-16-2661	*	**	**		
7aa	16+17	HF-16-1699	*	*	*	***	
7aa	11	HF-09-1341	*	*	*		
7aa	12	HF-09-963	***	**	**		
8	3	HF-57-3507	Rare				
8	14	HF-09-2515	**	***	***	*	
12	1	HF-18-2086	*****				
14-14wf	1	HF-20-3123	**	**	*	*	

Some of the features sampled consist of an individual microstratigraphic unit that is relatively homogeneous in content, and without bedding or lamination. We called

features in which this was the case “simple.” (Table S1). Other features display multiple, distinct microstratigraphic units, and they are usually richer in anthropogenic material.







**Fig. 6** Micromorphological characteristics of dump and scatter. Example of dump from GH 7aa feature 16 (HF-15–1198). **A** Abrupt contact with a more geogenic micro-unit (PPL and XPL). **B** Highly interconnected voids and spongy microstructure. Dark groundmass due to the high content of the organic material (PPL and XPL). **C** Burnt anthropogenic material, such as charred bones (bb), fat-derived char (fch) and charcoals (ch). **D** Thin cappings on charred ivory fragments. Example of scatter from GH 7a feature 10 (HF-20–3336). **E** and **F** Strong geogenic input preserving the characteristics of the geogenic microunit, such as a granular microstructure (PPL and XPL). **F** Less anthropogenic components mainly charred bones (bb) and charred material (fch) (PPL and XPL). **G** Rolling pedofeatures, such as calcitic coatings (PPL and XPL)

We call features that exhibit more than one microstratigraphic unit “complex”. Some complex features contain multiple microstratigraphic units that are solely classified as type 1, whereas others contain multiple microstratigraphic units classified as both type 1 and type 2.

### Elemental characterization and degree of manganese staining

Mapping elemental distributions on the thin sections using  $\mu$ XRF helped to identify and quantify the degree of manganese (Mn) staining that affects the bones and distinguishes it from colour changes due to heating (Shahack-Gross et al. 1997; Villagran et al. 2017). The area scans (Fig. 8) from two thin sections (HF-572 from GH 3cf and HF-15–1198 from GH 7aa Bef 16) revealed the presence of concentrations of several elements within the sediment and on the bone fragments. In sample HF-572 (GH 3cf) (Fig. 7), from the Gravettian layer GH 3cf, the first elemental map A.2 displays a high concentration of phosphorous (P) due to the high content of bones fragments (consisting mainly of hydroxylapatite). In thin section, these bones appear burnt, mainly at low temperature, with medium yellow to black colours visible (Villagran et al. 2017). Looking at the following scan A.3 (Fig. 8), the areas enriched in Mn appears to be the top and bottom of the thin section and not in the middle where the concentration of bones is higher. Even looking at sample HF-15–1198 (GH 7aa Bef 16), the ivory fragments appear dark brown to black in the thin section scan (Fig. 4B). However, the micro-XRF map shows Mn staining on the edge of the fragments and along the incremental bands of the ivory fragments (see the detail area in B.4 and B.5 from Fig. 8). Thus, in both samples, the dark colour seems to be due to burning and only superficially to staining, as in the case of HF-15–1998 (GH 7aa Bef 16) where the presence of Mn does not cover the entire surface.

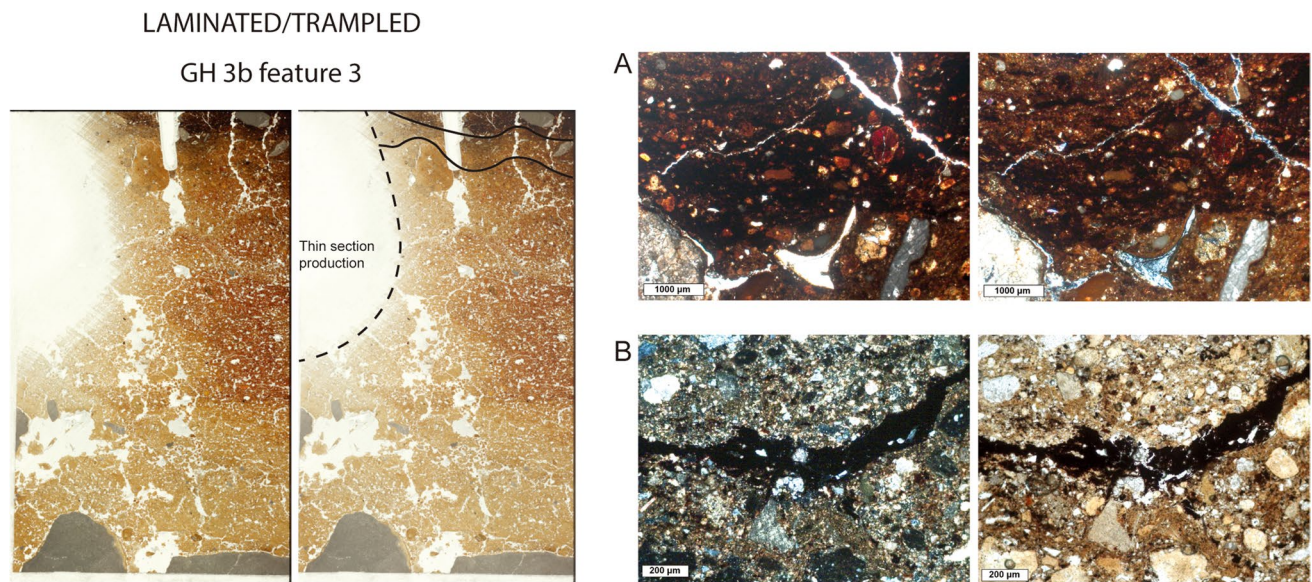
### Fabric analysis

For the fabric analysis, we used orientation data measured from lithic and faunal artefacts (Table 4). We selected

GH 7, 7a, 7aa and 14 and their features bef 6, bef 7, bef 16 and bef 1, because these layers and features had the most extensive data on elongated artefacts, making statistical analysis of the results possible. The 3D model of plots and features (Supplementary information Fig. S1) clearly shows the 15 degree slope to the deposits at Hohle Fels, as reported by Goldberg et al. (2003) and Schiegl et al. (2003). To investigate to what extent the natural slope impacted the fabric of material contained within the features, we first tested the archaeological material from outside the features but within the corresponding GH. In terms of horizontal bearing of the artefacts, the Rayleigh test failed to detect any non-uniform patterning in GH 7. However, Kuiper’s test indicates that the artefacts from outside the features have non-uniform distribution. This is more clearly visualized in the rose diagram of the bearing (Fig. 9). Overall, the artefacts from outside the features in GH 7, 7a and 7aa are not aligned horizontally. We have a not uniform orientation. The density plots of the bearing for these layers often show a bimodal distribution. GH 7 shows a preferred orientation dipping to the northwest at  $\sim 300^\circ$  (Table 4), while GH 7a and 7aa have a preferred orientation, with a dominant cluster facing southwest at  $\sim 210^\circ$  (Table 4). Data from GH 14 in contrast paint a different picture with its confidence interval from the Benn diagram closer to the planar pole than the other levels. The anthropogenic material from GH 14 exhibits a more uniform orientation and does not show a bimodal distribution. However, the density plot of the bearing displays a preferred pattern ( $\sim 300^\circ$ ).

Regarding the data on plunge, we see a higher plunge variance (Table 4) that might reflect an uneven, rugged surface morphology (Li et al. 2021) for GH 7, 7a and 7aa. For GH 14, as for the bearing, the plunge differs from the other layers (Table 4). Its plunge mean registers  $13.3^\circ$ , while the plunge variance is  $11.6^\circ$ . However, this data still indicates a certain unevenness of the ground surface. Usually, a flat surface shows a lower average plunge angle (Li et al. 2021).

Following our analysis of artefacts from outside the features, we focused our fabric analysis on archaeological material contained within the features. In terms of horizontal bearing within the features, the Rayleigh test reveals no non-uniform patterning from features 6 (GH 7) and 1 (GH 14). Instead, Kuiper’s test suggests that all the features, except feature 1 (GH 14), reject the null hypothesis. As for the analysis on artefacts outside of the feature, the fabric analysis of artefacts from within the features from GH 7, 7a and 7aa are not horizontally aligned (McPherron 2005, 2018; Li et al. 2021) and not close to a horizontal surface. The density histograms (Fig. 10) of the bearing do not always show a bimodal distribution. We observe bimodal distribution only in features GH 7 bef 6 and GH 7a bef 7. The bearing (Table 5) displays a slightly



**Fig. 7** Micromorphological characteristics of laminated/trampled feature from GH 3b feature 3 (HF-10–304). **A** Black groundmass showing lamination and a massive microstructure (PPL and XPL). **B** Charred material (PPL and XPL)

preferred orientation dipping in features 6 (GH 7) and 1 (GH 14) with a dominant cluster at  $\sim 280^\circ$  (west) and features 7 (GH 7a) and 16 (GH 7aa) clusters at  $\sim 210^\circ$  (south-west). As we observed in the fabric analysis of artefacts from outside the features, the analysis features 6, 7 and 16 from display an average plunge angle greater than  $15^\circ$  with considerable variance. In contrast, feature 1 from GH 14 preserves an average plunge angle equal to  $11^\circ$  (Table 5) and a plunge variance at  $9^\circ$ .

The Benn diagrams (Table 5) of the archaeological material from the GH (7, 7a, 7aa and 14) and the features (6, 7, 16 and 1) do not plot close to the planar pole. Only GH 14 and its feature (1) are relatively close to it. The confidence intervals associated with the material from outside the features (Fig. 10) almost completely overlap with orientation configurations associated with a debris flow. In contrast, the material from the features plots in a different position compared with the material from outside the features. Features 6 (GH7) and 7 (GH7a) plot outside the debris flow area, and feature 16 (GH 7aa) lies inside the debris flow area but closer to solifluction. Feature 1 (GH 14) overlaps with the water runoff area.

## Discussion

A geoarchaeological and microscopic analysis of combustion features is important for understanding the role played by the site in the life of the hunter-gatherer groups and the activities that took place there (Goldberg et al. 2009;

Aldeias et al. 2012; Miller et al. 2013; Karkanas et al. 2015; Stahlschmidt et al. 2015; Leierer et al. 2019). At Hohle Fels, our data allows us to reconstruct the formation history of these features which in turn can provide information on hominin behaviour and the location of the occupation.

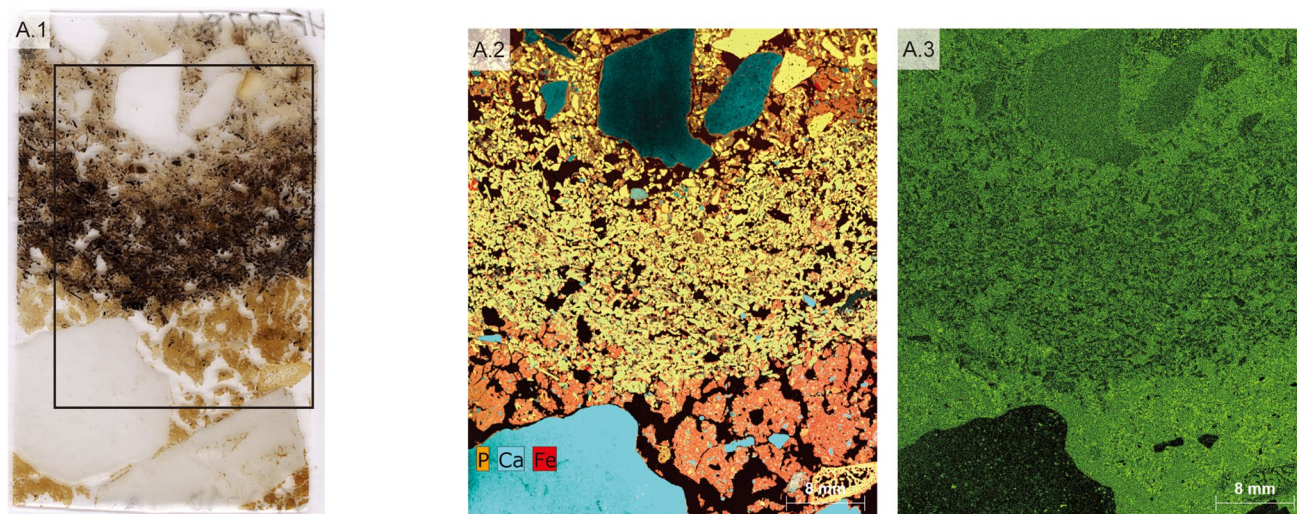
## Combustion features

Using micromorphology, we have identified three types of microstratigraphic units. The first type appears as a relatively thick layer with a strong anthropogenic input, a chaotic arrangement of the components, showing different degrees of heating, and no burned substrate. Thus, type 1 displays typical characteristics of material that has been subjected to dumping (Miller et al. 2010; Mallol et al. 2017) (Fig. 6). Type 2 has similar properties to dumping. However, the anthropogenic input is lower; thus, the geogenic part determines the patterning and texture of the thin section. The anthropogenic material still shows clear signs of combustion and a random orientation and distribution. We call this type of microstratigraphic unit scatter (Fig. 6). The third type of microstratigraphic unit (Fig. 7) exhibits a horizontal orientation of the components and laminated bedding structures reminiscent of deposits described by Banerjea et al. (2015) as trampled occupation deposits. We referred to this type as laminated deposit (Banerjea et al. 2015). Unfortunately, we identified this last type in only one thin section from a thin and small feature (GH 3b bef 3).

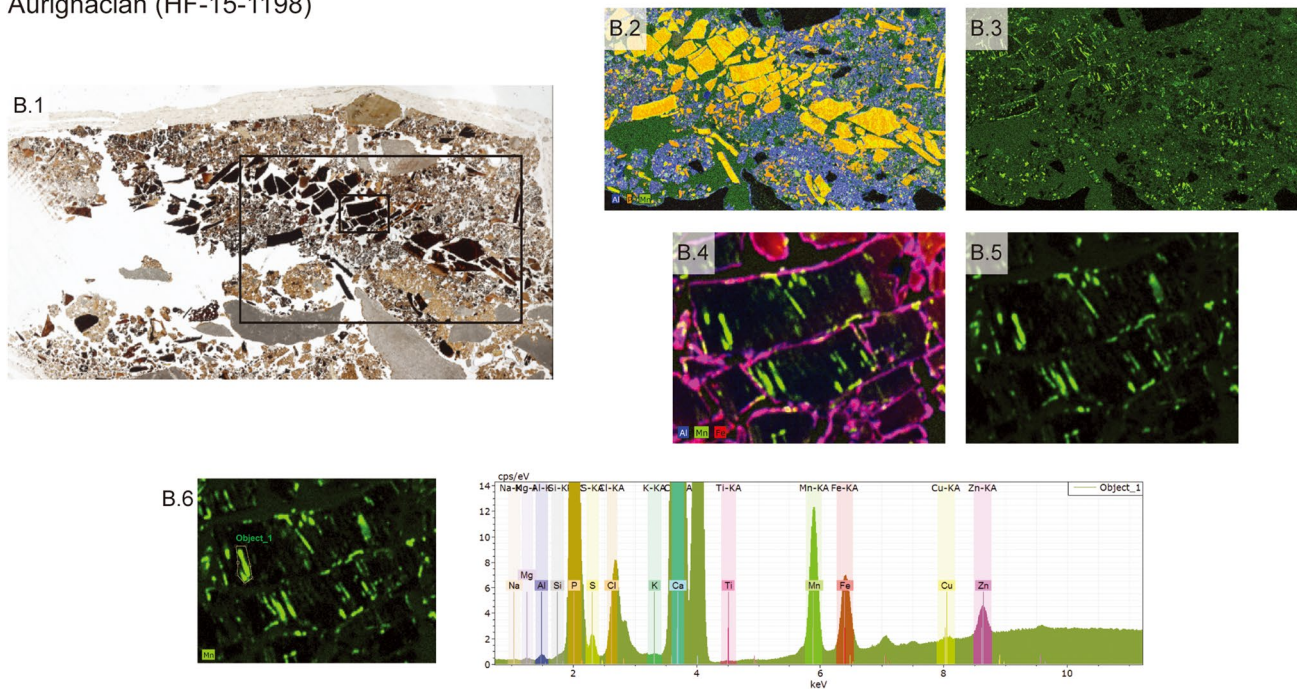
At Hohle Fels, the features usually have a considerable lateral extension. They often cover 1 or 2 square metres (up to 20 square metres as in the case of the Gravettian 3cf).



Gravettian (HF-527)



Aurignacian (HF-15-1198)



**Fig. 8** (A.1) Scan of thin section HF-572 from the Gravettian layer GH 3cf AH IIcf. In (A.2) note the micro-X-ray fluorescence (XRF) elemental maps showing the spatial distribution of phosphate (P) in yellow, calcium (Ca) in light blue and iron (Fe) in red and in (A.3) the spatial distribution of manganese (Mn) in green. (B.1) Scan of thin section HF-15–1198 from the Aurignacian GH 7aa feature 16. In (B.1) note the micro-XRF elemental maps showing the spatial

distribution of aluminum (Al) in dark blue, phosphate (P) in yellow-orange and manganese (Mn) in green, while in (A.3), only manganese (Mn) in green. Note the micro-XRF elemental maps A detail area of thin section HF-15–1198. (B.4) shows the concentration of aluminum (Al), manganese (Mn) and iron (Fe). (B.5) shows only the distribution of Mn. In (B.6) the micro-XRF spectra of the area outlined as Object\_1 within the scan. See the high content of Mn

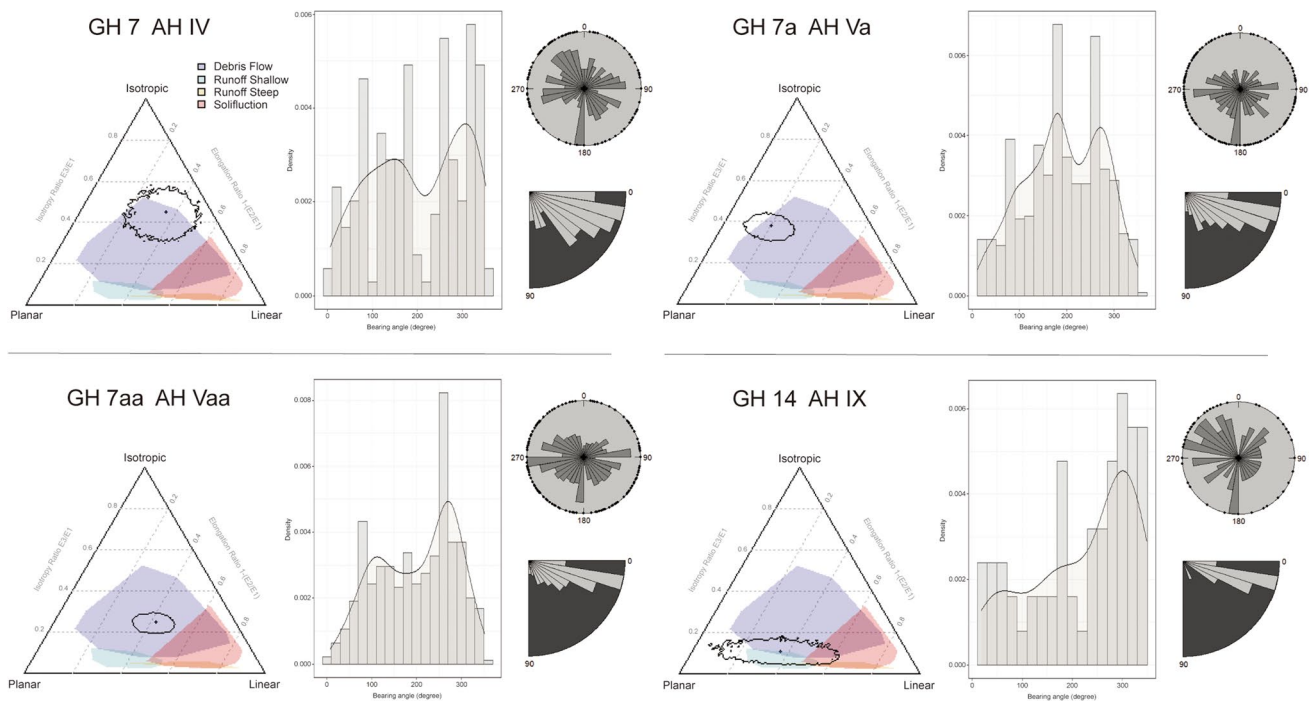
Several of our samples come from the same feature, and we note that it is relatively common that features include microstratigraphic units indicative of both dumping (type 1) and

scatters (type 2). For this reason, it is not possible to ascribe a single feature to a single type. The variation in microstratigraphic type within a single feature is likely impacted by the



**Table 4** Summary of archaeological orientation (lithics and bones) at Hohle Fels in the geological horizons (GH)

GH	N	Bearing				Plunge			
		Mean	Var	Mean res length	<i>P</i> (Rayleigh)	Mean	Var	Mean res length	<i>P</i> (Rayleigh)
7	173	307.9	52.8	0.08	0.34	25.1	21.6	0.93	<0.01
7a	679	201.8	40.9	0.29	<0.01	21.9	20.2	0.94	<0.01
7aa	474	224.4	44.5	0.22	<0.01	19.5	18.2	0.95	<0.01
14	63	298.4	40.7	0.29	0.01	13.3	11.6	0.98	<0.01

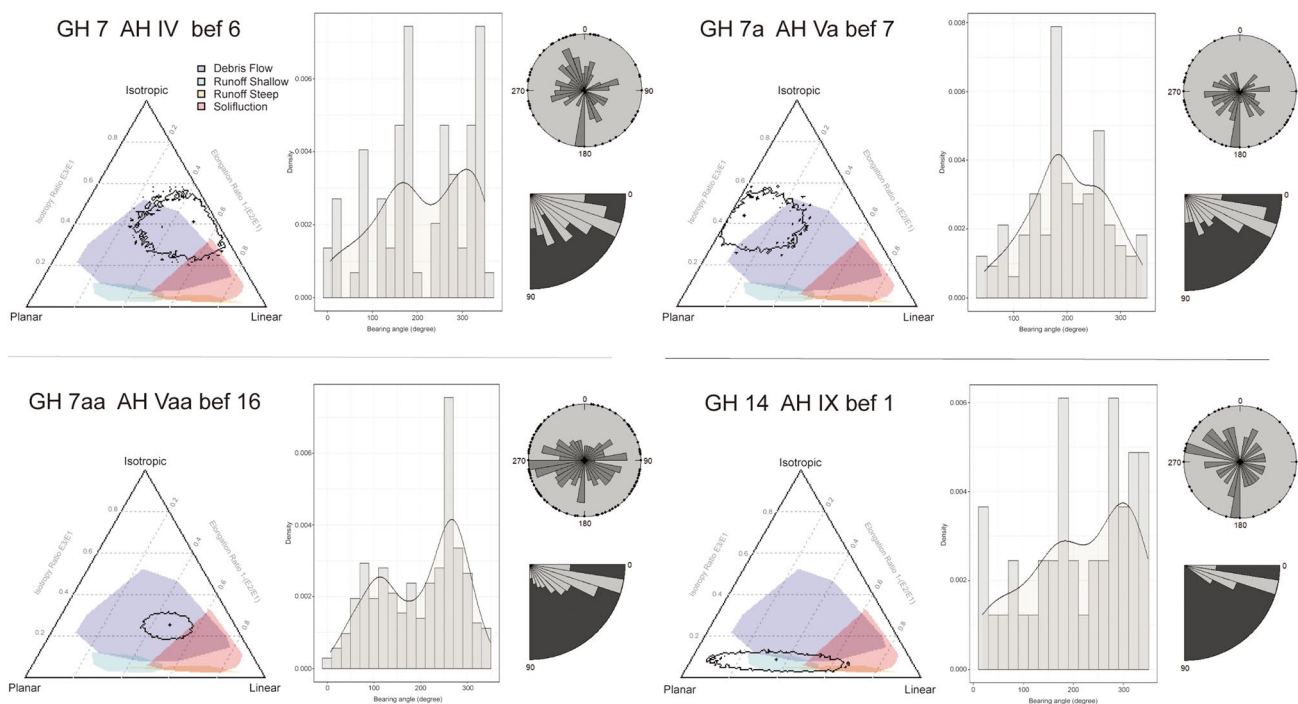
**Fig. 9** Orientation analysis of the elongated archaeological material from the geological horizon 7, 7a, 7aa, and 14

position of the samples (Fig. 11). Moreover, the complexity of the features showed that in the same thin section, we have microunits recording a sequence of dumping and scatter. Dumping and scatter appear as two facies genetically linked to the same anthropogenic activity, but which exhibit lateral variation and a repetitive occurrence. Thus, the dumping process at Hohle Fels produce a set of depositional processes (dumping and scatter) acting at the same time.

### Burnt material and fuel strategies

Our micromorphological analysis also demonstrated that one of the main discarded materials in these features is bone. Bones appear in all thin sections as a mix of different sizes and degrees of burning temperatures (Villagran et al. 2017), from low to high temperatures. Results from the  $\mu$ XRF elemental mapping suggest that some, but not all, of the colour change observed in the bone fragments can be attributed to manganese staining, suggesting that burning is the primary

cause of the dark colour. Manganese oxides, when present, do not penetrate into the bone but are only found on the edges of the bone fragments in thin section (Fig. 8). Thus, the material was first burnt and then underwent post-depositional oxide staining. Some degree of Mn staining is a common feature in middens along with chemical weathering and iron staining (Macphail and Goldberg 2010). Charcoal is present, often in association with the bone fragments, but in significantly smaller amounts. Charcoal dominates only one feature, from the Aurignacian GH 6 Bef 1 (Miller 2015). This feature is also the only feature that includes preserved ash rhombs. We rarely found ash rhombs within the feature of Hohle Fels. What we found in some features (GH7 Bef 1 and GH7 Bef 3 and 3cf) is a groundmass enriched in calcium carbonate. It is possible that this calcareous ground mass represents plant-derived ash that underwent some degree of dissolution and recrystallization. Due to the high quantity of bones, especially in 3 cf, the presence of this calcareous groundmass could provide, in rare cases, one of the few



**Fig. 10** Orientation analysis of the elongated archaeological material from the features 6, 7, 16, and 1

**Table 5** Summary of archaeological orientation (lithics and bones) at Hohle Fels in the features (Bef)

GH feature	N	Bearing				Plunge			
		Mean	Var	Mean res length	P (Rayleigh)	Mean	Var	Mean res length	P (Rayleigh)
7_Bef6	74	278.1	49.7	0.13	0.28	27.2	24.3	0.91	<0.01
7a_Bef7	132	204	34	0.41	<0.01	25.6	22	0.93	<0.01
7aa_Bef16	286	230.7	44.3	0.23	<0.01	20.5	18.8	0.95	<0.01
14_Bef1	41	279.5	46.4	0.19	0.23	11	9	0.99	<0.01

pieces of evidence that plant material was also burnt along with the bones (Schiegl et al. 2003; Miller 2015).

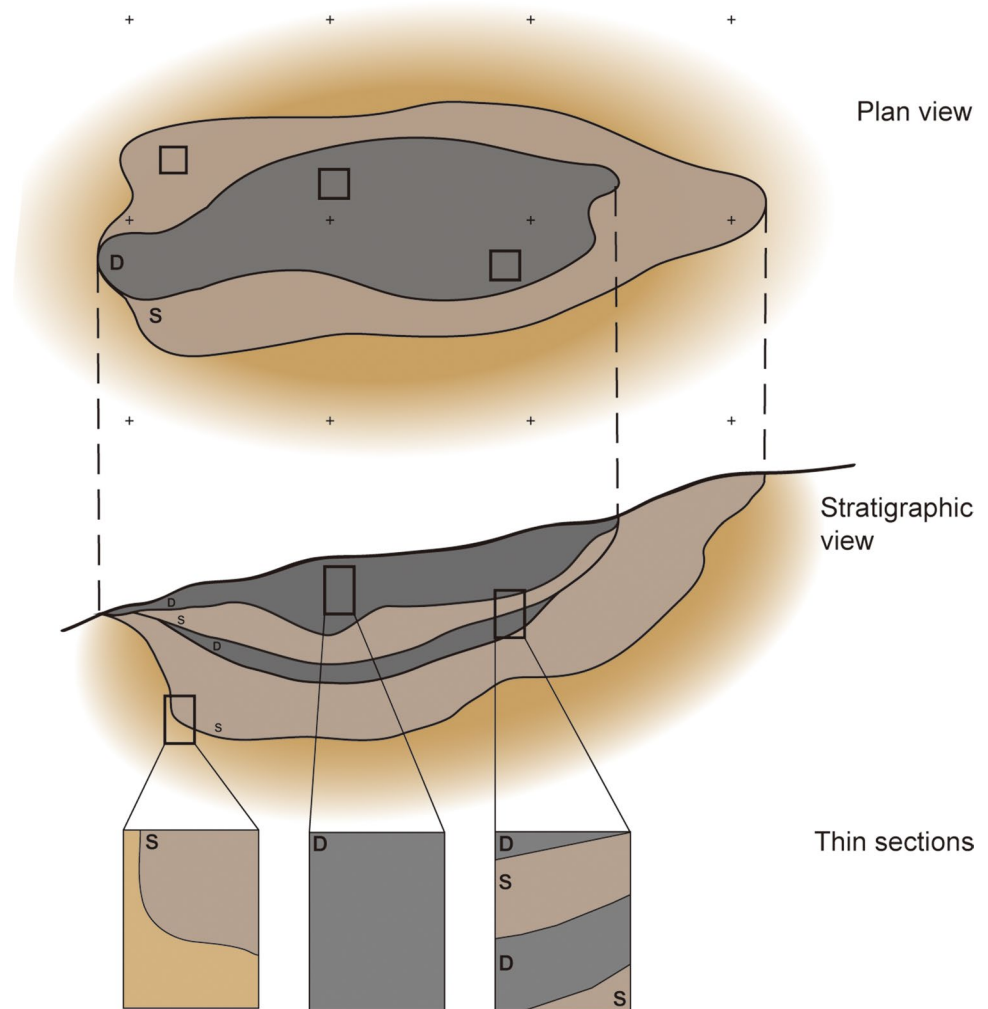
One hypothesis attempting to explain the dominance of charred bone over charcoal in the features at Hohle Fels (Schiegl et al. 2003; Miller 2015) is that this reflects choices in the type of fuel used for domestic hearths (Théry-Parisot 2002; Costamagno et al. 2005; Théry-Parisot et al. 2005). Both Miller (2015) and Schiegl et al. (2003) associated this assumption with environmental conditions (Riehl et al. 2015), arguing that glacial conditions would have reduced the availability of wood as a fuel, forcing occupants to rely on bone (Schiegl et al. 2003; Miller 2015). However, we observe no significant diachronic change in the proportion of charred bone found within the features that could be correlated with changing environmental conditions (Miller 2015). Other possible explanations for the high number of charred bones is the function of the fireplaces themselves (Théry-Parisot 2002),

bone marrow procurement (Binford 1981) or the burning of food refuse for site maintenance and the consequential waste removal (Costamagno et al. 2005; Bosch et al. 2012; Starkovich et al. 2020). More detailed taphonomic analysis of the faunal assemblages at Hohle Fels is needed to test these various possibilities.

**Degree of slope reworking**

Fabric analysis assumes that in situ assemblages share two determining characteristics: a randomly distributed bearing and a constrained dip arrangement (McPherron 2018). This assumption is true when the surfaces are flat and have a uniform relief (Li et al. 2021). If the surface is already a slope, the material would likely exhibit a non-uniform bearing arrangement in relation to its inclination, without the involvement of post-depositional alterations (McPherron 2005). A deeper analysis of the orientation of artefacts

**Fig. 11** Lateral and vertical variation model. The variation in microstratigraphic type within a single feature is likely impacted by the position of the samples. Thin sections preserving dumping (D) evidence come from the central area of the features and include the middle part of the feature section. On the other hand, samples with scattering (S) remains are either from very small features or from a more peripheral area of a larger feature, or they include the upper or the lower interfaces



from GHs and related features at Hohle Fels exhibit a different plunge and bearing configuration, particularly inside the features. While the material from each GH (7, 7a, 7aa) lies in the Benn diagram within the debris flow area, by analysing only the features the situation changes. In general, for features 6 (GH 7) and 7 (GH 7a), the orientations show higher values for both isotropy ratio and elongation (especially Bef 7), bringing the interval of confidence outside the area of the debris flow. Instead, features 16 (GH 7aa) and 1 (GH 14) appear more affected by other processes. Feature 16 (GH7aa) remains in the debris flow area, but it is closer to the solifluction area. Feature 1 (GH 14) overlaps more with the shallow runoff area.

The main processes of sediment accumulation within Hohle Fels are directly tied to the slope of the deposits which has a NW orientation and approximately 15° of inclination (Goldberg et al. 2003; Schiegl et al. 2003; Miller 2015). For this reason, we must consider several factors if we want to define whether these features are the result of slope movement or not. Micromorphological analysis suggests that these features are the outcome of dumping, an action that occurred on

an irregular and inclined surface. However, on a micro- and macro-scale, dumping and slope movements exhibit similar characteristics (Bertran et al. 1995; Bertran and Texier 1995, 1999), a similarity that in our case might be higher since the previous surface has a strong impact on the orientation of the clasts (McPherron 2005, 2018; Li et al. 2021). In only two GHs (7 and 14), the material has a bearing mean (~300) following the slope orientation (NW), towards the entrance of the cave. The other two GHs (7a and 7aa) maintain a lower bearing mean with a south-west orientation. By analysing the feature only, we see the bearing mean decreasing. It decreases towards the west in GH 7 and 14 and towards the south-west direction in GH 7a and 7aa. The impression is that the material in the features is less affected by the orientation of the slope. On the plunge, both GHs and features show an average angle greater than 10°. The plunge keeps a very high plunge mean for GH 7, 7a and 7aa (Table 3) and their features (Table 4), with high plunge variation. This high plunge variance is probably linked to a greater irregularity of the initial surface morphology (Li et al. 2021). Thus, we have a higher plunge compared to the plunge of the slope and high variability.



GH 14 and its feature 1 differ from the others. They have a lower plunge mean ( $\sim 11^\circ$ ), which most resembles the slope inclination at Hohle Fels and a lower plunge variance ( $\sim 9^\circ$ ). Both GH and feature seem to be more affected by the slope conformation and natural processes (Bertran et al. 1997; Lenoble and Bertran 2004). Their intervals of confidence lie within the water runoff area in the Benn diagram. Observation that is consistent with what we see in thin section. In thin section, GH 14 Bef 1 shows three different microunits. In particular, the middle microunit, rich in anthropogenic material both charred and unburnt, and the upper microunit, characterized by a geogenic input, show a clear imbrication of the coarse fraction. Burnt material and limestone fragments have a parallel distribution and a slightly oblique orientation.

In general, Benn diagrams and bearing-plunge analysis suggest a certain degree of reworking by the slope for the GHs. They all lie within the debris flow area, and the bearing tends to be NW oriented. Only the plunge shows a shift away from the characteristics of the slope. For the features, the situation is different. For example, the confidence interval of features 7 (GH 7a) and 6 (GH 7) plots outside the debris flow area. Additionally, bearing and plunge do not match with the slope properties from Hohle Fels. Apart from feature 1 (GH14), they have a more random and chaotic bearing and plunge, which is reminiscent of micro- and macroscale characteristics of dumping (Karkanas et al. 2012), especially if the material has accumulated on an already uneven and sloping surface. Therefore, we can assume that, at least for the Upper Palaeolithic features, the main depositional agent is human and argue that the features are close to their primary position of dumping.

### Occupation pattern and mobility

A long history of investigation at Hohle Fels (Fraas 1872; Hahn 1977; Conard et al. 2001, 2002, 2003; Conard and Bolus 2008; Conard and Uerpmann 2000; Conard et al. 2021; Miller 2015), but also the nearby sites of Sirgenstein (Schmidt 1912) and Geißenklösterle (Hahn et al. 1978; Conard et al. 2019), demonstrate a significant difference in artefact densities between the Middle and Upper Palaeolithic of the Ach Valley and the Swabian Jura in general (Conard 2011; Conard and Bolus 2003; Conard et al. 2006, 2012, 2021). Conard (2011) reports artefact densities an order or two of magnitude lower for the Middle Palaeolithic at Hohle Fels, compared to the Upper Palaeolithic. Even for the recently excavated layer AH XI, GH14—which contains Blattspitzen and combustion features (Conard et al. 2021)—the artefact densities still remain significantly lower than what is found in the Aurignacian occupations. This pattern of the Middle to Upper Palaeolithic transition in Swabia led Conard and others (Conard 2011; Conard and Bolus 2003;

Conard et al. 2006, 2012, 2021; Miller 2015 as well) to suggest that the occupational intensity and use of the cave sites varied between Neanderthals and the first modern humans, with Neanderthals repeatedly visiting the sites, but for relatively short periods and as small groups (Conard et al. 2006, 2012, 2021), when compared to the Upper Palaeolithic occupations. Additionally, the stratigraphic separation of the Middle from the Upper Palaeolithic implied that there was relatively little interaction between these two forms of humans in southern Germany, prompting the formulation of the Kulturpumpemodell (Conard et al. 2006) and the Danube Corridor Hypothesis, which argued that Neanderthals were either absent or present in significantly low population numbers, thereby facilitating the rapid and early movement of modern humans into the area.

The concept of occupational intensity, which is often linked with settlement and mobility patterns within hunter-gatherer groups (Wadley 2001; Munro 2004; Henshilwood 2005; Conard 2011, and Conard 2004 for a complete review), generally employs artefact densities as an index for population size and length of occupation (Varis et al. in review, Varien and Mills 1997, Henshilwood et al. 2001, Wurz 2002, Will et al. 2014; Reynard et al. 2016). However, estimating occupational intensity of a site solely on the basis of artefact densities can be difficult, since density of finds can be influenced by a number of factors, such as changing sedimentation rates (Jerardino 2016), changes in lithic technological practices (Hiscock 1981) and varying spatial distributions of activities across a site (Domínguez-Rodrigo and Cobo-Sánchez 2017), among others (Haaland et al. 2021, Varis et al. in review). Furthermore, the concept of occupational intensity itself, particularly for mobile hunter-gatherer groups, covers a range of different variables, such as the length of occupation, the frequency of occupation and group size (Munro 2004; Conard 2011).

Another means of investigating occupational intensity besides artefact density is through site-structure analysis (Haaland et al. 2021, Kelly 1992, Koetje 1994). These types of studies generally tend to rely on ethnographic and ethnoarchaeological data that suggest that the placement of features such as hearths, the spatial separation of activities and the distance of waste disposal locations from the centre of the camp reflect group size and the length of occupation (Yellen 1977; Brooks and Yellen 1987; Murray 1980; Hardy-Smith and Edwards 2004) and can therefore potentially be used to assess residential mobility (Kelly 1992). Micromorphological analysis of anthropogenic features has also recently contributed to our understanding of the relationship between site structure, occupational intensity and hunter-gatherer mobility in the archaeological record (Goldberg et al. 2009; Miller 2015; Miller et al. 2013; Haaland et al. 2021; Marcuzzan et al. 2022; Leierer et al. 2019; Aldeias et al. 2012). By providing a high-resolution

view of the formation history of an anthropogenic feature, micromorphology can help determine if features represent intact hearths, ash dumps (Schiegl et al. 2003), trampled surfaces (Marcazzan et al. 2022) or single- or multiple use hearths (Leierer et al. 2019; Haaland et al. 2021).

At Hohle Fels, previous micromorphological analyses of several features from the Upper Palaeolithic occupations suggest that they formed largely through anthropogenic dumping (Schiegl et al. 2003; Miller 2015). The current study, which significantly expanded the number of features analysed and assessed their formation history using micromorphology in combination with fabric analysis, generally confirms this interpretation. Overall, the area of Hohle Fels currently under excavation seems to have been used for the dumping of waste associated with combustion residues, at least largely during the Upper Palaeolithic. The attribution of this area as a waste disposal zone (Schiegl et al. 2003; Miller 2015) would suggest that the area of occupation was likely elsewhere within the cave, probably closer to the entrance (Schiegl et al. 2003). These observations would suggest that Upper Palaeolithic occupation of Hohle Fels had clearly defined division of space and may imply longer periods of occupation (Yellen 1977; Brooks and Yellen 1987) or possibly higher population densities (Wilson 1994; Kent 1999), a pattern that fits with previous interpretations of changes in occupation intensity across the Middle to Upper Palaeolithic transition at Hohle Fels (Conard et al. 2006; Conard 2011; Conard et al. 2012). Below the Aurignacian layers, dumped features, and combustion features in general, are generally absent from the Middle Palaeolithic (GH13 to GH9). This observation generally mirrors the low density of finds in Hohle Fels (Conard et al. 2021) and in Swabian Jura (Conard et al. 2006; Conard 2011) during the later phases of the Middle Palaeolithic. The recent excavation of GH 15 and GH 14 document a higher density of finds, together with *Blattspitzen* and a combustion feature, suggesting that there may have been phases of more intensive occupation of the site by Neanderthals as well (Conard et al. 2021).

## Conclusions

Research at Hohle Fels allows us to examine a large number of combustion features within an archaeologically rich Pleistocene deposit. Through micromorphological analysis, we identify three different types of features: (1) dumped features, (2) scattered residues from combustion features and (3) laminated and trampled features. However, while establishing a difference between dumped and scattered materials, we noted that both were closely related to each other. Both vertically and laterally, we found that the features often preserved both, sometimes even in the same thin section. This observation underlines their belonging

to the same depositional process. Among the 16 studied features, one preserves evidence of a laminated trampled surface (GH 3b Bef 3), while the other 15 are the result of dumping. We found a similar uniformity in the burnt material. The 15 dumped features studied here exhibit similar composition over the entire stratigraphic sequence. Charred bones, resulting from combustion at low to high temperatures, imply the systematic use of bones for fuel. The only exception is GH 6a Bef 1 (thin section HF-76-1246B, scan in supplementary information), where charcoal and ash are dominant.

The orientation analysis of bones and lithic artefacts shows that the archaeological material from outside the features (the Aurignacian GH 7, 7a, 7aa and the Middle Palaeolithic GH 14) underwent a certain degree of slope reworking. This observation is also true for the Middle Palaeolithic feature 1 in GH 14, which appears to have been subjected to some relocation caused by slope wash. In contrast, the Aurignacian features (6 in GH 7, 7 in GH 7a and 16 in GH 7aa) generally preserve the original fabric of dumped deposits without reworking from the slope. Thus, the effects of post-depositional processes on the features are generally limited, at least for those from the Upper Palaeolithic occupations. Our results here suggest that throughout the Upper Palaeolithic, and also Middle Palaeolithic, people repeatedly disposed of their waste within a particular part of Hohle Fels and despite the high density of combustion residues, most of the burning, and thus occupation, took place elsewhere within the cave.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s12520-022-01647-7>.

**Acknowledgements** Panos Kritikakis produced the thin sections included in this work at the Geoarchaeology Laboratory of the University of Tübingen. The authors are grateful to the excavation team of Hohle Fels, especially to Maria Malina and Alexander Janas (University of Tübingen) for the access to the field descriptions from Hohle Fels, the 3D model and the technical support. Further, the authors would like to express their gratitude to Susan M. Mentzer for the support given with the micro-XRF analysis, Li Li for the essential advice and comments on the orientation analysis and Paul Goldberg for many productive discussions and constructive comments on our work at Hohle Fels. We also thank the 2 anonymous reviewers for their valuable comments.

**Author contribution** Each of the co-authors has made substantial contributions to this manuscript and has approved this final version. Diana Marcazzan and Christopher E. Miller designed the research; Nicholas J Conard coordinated the field work at Hohle Fels; Diana Marcazzan and Christopher Miller performed the micromorphological analysis; Diana Marcazzan performed the fabric analysis and interpreted the micro-XRF data; all the co-authors wrote the paper.

**Funding** Open Access funding enabled and organized by Projekt DEAL. This research was funded by the Baden-Württemberg Ministry of Culture and Science, doctoral scholarship granted to D. Marcazzan into the Evolution of Cultural Modernity research project (University of Tübingen).



**Data availability** All data is provided as supplementary materials attached to this submission.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Aldeias V, Goldberg P, Sandgathe D et al (2012) Evidence for Neanderthal use of fire at Roc de Marsal (France). *J Archaeol Sci* 39:2414–2423. <https://doi.org/10.1016/j.jas.2012.01.039>
- Angelucci DE (2017) Lithic artefacts. In: *Archaeological Soil and Sediment Micromorphology*. John Wiley & Sons, Ltd, Chichester, pp 223–229
- Banerjee RY, Bell M, Matthews W, Brown A (2015) Applications of micromorphology to understanding activity areas and site formation processes in experimental hut floors. *Archaeol Anthropol Sci* 7:89–112. <https://doi.org/10.1007/s12520-013-0160-5>
- Barbieri A, Leven C, Toffolo MB et al (2018) Bridging prehistoric caves with buried landscapes in the Swabian Jura (southwestern Germany). *Quat Int* 485:23–43. <https://doi.org/10.1016/j.quaint.2017.08.002>
- Barbieri A, Bachofer F, Schmaltz EM et al (2021) Interpreting gaps: a geoarchaeological point of view on the Gravettian record of Ach and Lone valleys (Swabian Jura, SW Germany). *J Archaeol Sci* 127:105335. <https://doi.org/10.1016/j.jas.2021.105335>
- Bataille G, Conard NJ (2018) Blade and bladelet production at Hohle Fels Cave, AH IV in the Swabian Jura and its importance for characterizing the technological variability of the Aurignacian in Central Europe. *PLoS One* 13:e0194097. <https://doi.org/10.1371/journal.pone.0194097>
- Baykara İ, Mentzer SM, Stiner MC et al (2015) The Middle Paleolithic occupations of Üçağızlı II Cave (Hatay, Turkey): geoarchaeological and archeological perspectives. *J Archaeol Sci Rep* 4:409–426. <https://doi.org/10.1016/j.jasrep.2015.09.022>
- Benito-Calvo A, Martínez-Moreno J, Jordá Pardo JF et al (2009) Sedimentological and archaeological fabrics in Palaeolithic levels of the South-Eastern Pyrenees: Cova Gran and Roca dels Bous Sites (Lleida, Spain). *J Archaeol Sci* 36:2566–2577. <https://doi.org/10.1016/j.jas.2009.07.012>
- Benn D (1994) Fabric shape and the interpretation of sedimentary fabric data. *J Sediment Res* 64:910–915
- Bentsen SE (2014) Using pyrotechnology: fire-related features and activities with a focus on the African middle stone age. *J Archaeol Res* 22:141–175. <https://doi.org/10.1007/s10814-013-9069-x>
- Berna F, Goldberg P (2008) Assessing Paleolithic pyrotechnology and associated hominin behavior in Israel. *Israel J Earth Sci* 56:107–121
- Bertran P, Texier J-P (1995) Fabric analysis: application to Paleolithic sites. *J Archaeol Sci* 22:521–535
- Bertran P, Texier J-P (1999) Facies and microfacies of slope deposits. *CATENA* 35:99–121
- Bertran P, Hetu B, Texier J-P, Steijn H (1997) Fabric characteristics of subaerial slope deposits. *Sedimentology* 44:1–16
- Bertran P, Francou B, Texier J-P (1995) Stratified slope deposits: the stone-banked sheets and lobes model. *Steepland Geomorph* 147–169
- Binford LR (1978) Dimensional analysis of behavior and site structure: learning from an Eskimo hunting stand. *Am Antiq* 43:330–361
- Binford LR (1981) *Bones: Ancient Men and Modern Myths*. Academic Press, New York
- Binford LR (1996) Hearth and home: the spatial analysis of ethnographically documented rock shelter occupations as a template for distinguishing between human and hominid use of sheltered space. In: Conard NJ, Wendorf F (eds) *Middle Paleolithic and Middle Stone Age settlement systems*. A.B.A.C.O. Edizioni, Forlì, pp 229–239
- Bosch MD, Nigst PR, Fladerer FA, Antl-Weiser W (2012) Humans, bones and fire: zooarchaeological, taphonomic, and spatial analyses of a Gravettian mammoth bone accumulation at Grub-Kranawetberg (Austria). *Quat Int* 252:109–121. <https://doi.org/10.1016/j.quaint.2011.08.019>
- Brönnimann D, Röder B, Spichtig N et al (2020) The Hidden Midden: geoarchaeological investigation of sedimentation processes, waste disposal practices, and resource management at the La Tène settlement of Basel-Gasfabrik (Switzerland). *Geoarchaeology* 35:522–544. <https://doi.org/10.1002/gea.21787>
- Brooks AS, Yellen JE (1987) The preservation of activity areas in the archaeological record: ethnoarchaeological and archaeological work in northwest Ngamiland, Botswana
- Canti MG (2003) Aspects of the chemical and microscopic characteristics of plant ashes found in archaeological soils. *CATENA* 54:339–361. [https://doi.org/10.1016/S0341-8162\(03\)00127-9](https://doi.org/10.1016/S0341-8162(03)00127-9)
- Canti MG (2017) Charred plant remains. In: *Archaeological Soil and Sediment Micromorphology*. John Wiley & Sons, Ltd, Chichester, pp 141–142.
- Conard NJ (2003) Palaeolithic ivory sculptures from southwestern Germany and the origins of figurative art. *Nature* 426:830–832. <https://doi.org/10.1038/nature02186>
- Conard NJ (2004) *Settlement dynamics of the Middle Paleolithic and Middle Stone Age*. Kerns Verlag, Tübingen
- Conard NJ (2009) A female figurine from the basal Aurignacian of Hohle Fels Cave in southwestern Germany. *Nature* 459:248–252. <https://doi.org/10.1038/nature07995>
- Conard NJ, Bolus M (2003) Radiocarbon dating the appearance of modern humans and timing of cultural innovations in Europe: new results and new challenges. *J Hum Evol* 44:331–371. [https://doi.org/10.1016/S0047-2484\(02\)00202-6](https://doi.org/10.1016/S0047-2484(02)00202-6)
- Conard NJ, Bolus M (2008) Radiocarbon dating the late Middle Paleolithic and the Aurignacian of the Swabian Jura. *J Hum Evol* 55:886–897. <https://doi.org/10.1016/j.jhevol.2008.08.006>
- Conard NJ, Kieselbach P (2006) Ein phallusförmiges steinwerkzeug aus den gravettienschichten des Hohle Fels. *Archaeologisches Korrespondenzblatt* 36:455–472
- Conard NJ, Uerpman H (2000) New evidence for Paleolithic rock painting in Central Europe. *Curr Anthropol* 41:853–856
- Conard NJ, Languth K, Uerpman H-P (2001) Die Ausgrabungen im Gravettian des Hohle Fels bei Schelklingen. *Alb Donau-Kreis Archäologische Ausgrabungen in Baden-Württemberg* 2000:18–22
- Conard NJ, Languth K, Uerpman HP (2002) Neue Aurignacian-Fundschichten im Hohle Fels bei Schelklingen, Alb-Donau-Kreis. *Archäologische Ausgrabungen in Baden-Württemberg* 2001:21–26

- Conard NJ, Bolus M, Münzel SC (2012) Middle Paleolithic land use, spatial organization and settlement intensity in the Swabian Jura, southwestern Germany. *Quat Int* 247:236–245. <https://doi.org/10.1016/j.quaint.2011.05.043>
- Conard NJ, Janas A, Marczasz D et al (2021) The cultural and chronostratigraphic context of a new leaf point from Hohle Fels Cave in the Ach Valley of southwestern Germany. *MGfU* 30:41–66
- Conard NJ, Bolus M, Goldberg P, Münzel SC (2006) The last Neanderthals and first modern humans in the Swabian Jura. 11th ICAZ International Conference Paris, 23–28 August 2010 Abstracts:113
- Conard NJ, Bolus M, Münzel S (2019) Geißenklösterle Chronostratigraphie, Palaoumwelt und Subsistenz im Mittel- und Jungpaläolithikum der Schwabischen Alb, tübinger monographien zur urgeschichte, Kerns verlag, Tübingen
- Conard, N.J. (2011). The demise of the Neanderthal cultural niche and the beginning of the upper Paleolithic in southwestern Germany. In: Conard, N.J., Richter, J. (eds) Neanderthal Lifeways, Subsistence and Technology. *Vertebr Paleobiology Paleoanthropology*. Springer, Dordrecht. [https://doi.org/10.1007/978-94-007-0415-2\\_19](https://doi.org/10.1007/978-94-007-0415-2_19)
- Costamagno S, Thery-Parisot I, Brugal J-P, Guibert R (2005) Taphonomic consequences of the use of bones as fuel. Experimental data and archaeological applications. In: *Biosphere to lithosphere: new studies in vertebrate taphonomy*. Oxbow Books Oxford, pp 51–62
- Courty MA, Goldberg P, Macphail R (1989) Soils and micromorphology in archaeology. Cambridge University Press, Cambridge
- Courty M-A (2001) Microfacies analysis assisting archaeological stratigraphy. In: *Earth Sciences and Archaeology*. Springer US, Boston, pp 205–239. [https://doi.org/10.1007/978-1-4615-1183-0\\_8](https://doi.org/10.1007/978-1-4615-1183-0_8)
- de la Torre I, Benito-Calvo A (2013) Application of GIS methods to retrieve orientation patterns from imagery; a case study from Beds I and II, Olduvai Gorge (Tanzania). *J Archaeol Sci* 40:2446–2457. <https://doi.org/10.1016/j.jas.2013.01.004>
- Dibble H, Berna F, Goldberg P, et al (2009) A preliminary report on Pech de l’Azé IV, layer 8 (Middle Paleolithic, France). *Paleo-Anthropology* 182–219 <https://doi.org/10.4207/PA.2009.ART30>
- Domínguez-Rodrigo M, Cobo-Sánchez L (2017) The spatial patterning of the social organization of modern foraging Homo sapiens: a methodological approach for understanding social organization in prehistoric foragers. *Palaeogeogr Palaeoclimatol Palaeoecol* 488:113–125
- Fraas O (1872) Resultate der Ausgrabungen im Hohlefels bei Schelklingen. *Jahresh Ver vaterl Nat.kd Wurt* 28:21–36
- Geyer OF, Gwinner MP (1991) *Geologie von Baden-Württemberg*, 5th edn. Schweizerbart’sche, E, Stuttgart
- Giusti D, Konidaris GE, Tourloukis V et al (2019) Recursive anisotropy: a spatial taphonomic study of the Early Pleistocene vertebrate assemblage of Tsiotra Vryssi, Mygdonia Basin, Greece. *Boreas* 48:713–730. <https://doi.org/10.1111/bor.12368>
- Goldberg P, Berna F (2010) Micromorphology and context. *Quat Int* 214:56–62
- Goldberg P, Schiegl S, Meline K et al (2003) Micromorphology and site formation at Hohle Fels cave, Swabian Jura, Germany. *Eiszeit Gegenw* 53:1–25
- Goldberg P, Miller CE, Schiegl S et al (2009) Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeol Anthropol Sci* 1:95–122. <https://doi.org/10.1007/s12520-009-0008-1>
- Goldberg P, Whitbread I (1993) Micromorphological study of a Bedouin tent floor. *Formation Processes in Archaeological Context*, Prehistory Press, Madison 165e188
- Haaland MM, Miller CE, Unhammer OF et al (2021) Geoarchaeological investigation of occupation deposits in Blombos Cave in South Africa indicate changes in site use and settlement dynamics in the southern Cape during MIS 5b–4. *Quat Res* 100:170–223. <https://doi.org/10.1017/qua.2020.75>
- Hahn J (1977) Fossilvergesellschaftungen Nr. 72. *Nachgrabungen im Hohlen Felsen bei Schelklingen*. Alb-Donau-Kreis Archäologisches Korrespondenzblatt Mainz 7:241–248
- Hahn J, von Koenigswald W, Wagner E, Wille W (1978) Das Geissenklösterle bei Blaubeuren, Alb-Donau-Kreis. Eine altsteinzeitliche Höhlenstation der mittleren Alb. *Fundberichte Aus Baden-Württemberg* 3:14–37
- Hardy-Smith T, Edwards PC (2004) The Garbage Crisis in prehistory: artefact discard patterns at the Early Natufian site of Wadi Hamme 27 and the origins of household refuse disposal strategies. *J Anthropol Archaeol* 23:253–289. <https://doi.org/10.1016/j.jaa.2004.05.001>
- Heckel C (2009) Physical characteristics of mammoth ivory and their implications for ivory work in the Upper Paleolithic. *Mitteilungen Der Gesellschaft Für Urgeschichte* 18:71–79
- Henshilwood CS, D’errico F, Marean CW et al (2001) An early bone tool industry from the Middle Stone Age at Blombos Cave, South Africa: implications for the origins of modern human behaviour, symbolism and language. *J Hum Evol* 41:631–678. <https://doi.org/10.1006/jhev.2001.0515>
- Henshilwood CS (2005) Stratigraphic integrity of the Middle Stone Age levels at Blombos cave. In: d’Errico F, Backwell L (eds) *From Tools to Symbols: From Early Hominids to Modern Humans*. Witwatersrand University Press, Johannesburg (2005), pp 441–458
- Hiscock P (1981) Comments on the use of chipped stone artefacts as a measure of “intensity of site usage”. *Aust archaeol* 13:30–34
- Jerardino A (2016) Shell density as proxy for reconstructing prehistoric aquatic resource exploitation, perspectives from southern Africa. *J Archaeol Sci Rep* 6:637–644. <https://doi.org/10.1016/j.jasrep.2015.06.005>
- Karkanas P (2002) Micromorphological studies of Greek prehistoric sites: new insights in the interpretation of the archaeological record. *Geoarchaeology* 17:237–259. <https://doi.org/10.1002/gea.10012>
- Karkanas P, Goldberg P (2018) Reconstructing archaeological sites: understanding the geoarchaeological matrix. John Wiley & Sons.
- Karkanas P, Dabney MK, Smith RAK, Wright JC (2012) The geoarchaeology of Mycenaean chamber tombs. *J Archaeol Sci* 39:2722–2732. <https://doi.org/10.1016/j.jas.2012.04.016>
- Karkanas P, Brown KS, Fisher EC et al (2015) Interpreting human behavior from depositional rates and combustion features through the study of sedimentary microfacies at site Pinnacle Point 5–6, South Africa. *J Hum Evol* 85:1–21. <https://doi.org/10.1016/j.jhevol.2015.04.006>
- Kelly RL (1992) Mobility/sedentism: concepts, archaeological measures, and effects. *Annu Rev Anthropol* 21:43–66
- Kent S (1999) The archaeological visibility of storage: delineating storage from trash areas. *Am Antiq* 64:79–94
- Koetje TA (1994) Intrasite spatial structure in the European Upper Paleolithic: evidence and patterning from the SW of France. *J Anthropol Archaeol* 13:161–169. <https://doi.org/10.1006/jaar.1994.1011>
- Kuhn SL, Stiner MC, Güleç E et al (2009) The early Upper Paleolithic occupations at Uçağizli Cave (Hatay, Turkey). *J Hum Evol* 56:87–113. <https://doi.org/10.1016/j.jhevol.2008.07.014>
- Leierer L, Jambrina-Enríquez M, Herrera-Herrera AV et al (2019) Insights into the timing, intensity and natural setting of Neanderthal occupation from the geoarchaeological study of combustion structures: a micromorphological and biomarker investigation of El Salt, unit Xb, Alcoy, Spain *Plos One* 14:e0214955. <https://doi.org/10.1371/journal.pone.0214955>
- Leierer L, Carrancho Alonso Á, Pérez L et al (2020) It’s getting hot in here – microcontextual study of a potential pit hearth at



- the Middle Paleolithic site of El Salt, Spain. *J Archaeol Sci* 123:105237. <https://doi.org/10.1016/j.jas.2020.105237>
- Lenoble A, Bertran P (2004) Fabric of Palaeolithic levels: methods and implications for site formation processes. *J Archaeol Sci* 31:457–469. <https://doi.org/10.1016/j.jas.2003.09.013>
- Lenoble A, Bertran P, Lacrampe F (2008) Solifluction-induced modifications of archaeological levels: simulation based on experimental data from a modern periglacial slope and application to French Palaeolithic sites. *J Archaeol Sci* 35:99–110. <https://doi.org/10.1016/j.jas.2007.02.011>
- Li L, Lin SC, Peng F et al (2021) Simulating the impact of ground surface morphology on archaeological orientation patterning. *J Archaeol Sci* 126:105310. <https://doi.org/10.1016/j.jas.2020.105310>
- Ligouis B (2017) Reflected light. In: *Archaeological Soil and Sediment Micromorphology*. John Wiley & Sons, Ltd, Chichester, pp 461–470.
- Lotter MG, Gibbon RJ, Kuman K et al (2016) A geoarchaeological study of the middle and upper Pleistocene levels at canteen kopje, northern cape province, South Africa. *Geoarchaeology* 31:304–323. <https://doi.org/10.1002/gea.21541>
- Macphail RI, Goldberg P (2010) Archaeological Materials. In: Stoops G, Marcelino V, Mees F (eds) *Interpretation of Micromorphological Features in Soils and Regoliths*. Elsevier, Amsterdam, pp 589–622
- Macphail RI, Goldberg P (2000) Geoarchaeological investigations of sediments from Gorham's and Vanguard Caves, Gibraltar: Microstratigraphical (soil micromorphological and chemical) signatures. In: Stringer CB, Barton RNE, Finlayson JC (eds) *Neanderthals on the Edge*. Oxbow Books, Oxford, pp 183–200
- Mallol C, Mentzer SM, Miller CE (2017) Combustion features. In: *Archaeological Soil and Sediment Micromorphology*. John Wiley & Sons, Ltd, Chichester, pp 299–330
- Mallol C, Mentzer SM (2015) Contacts under the lens: perspectives on the role of microstratigraphy in archaeological research. *Archaeol Anthropol Sci* 9:1645–1669. <https://doi.org/10.1007/s12520-015-0288-6>
- Marczazan D, Miller CE, Ligouis b, et al (2022) Middle and Upper Paleolithic occupations of Fumane Cave (Italy): a geoarchaeological investigation of the anthropogenic features. *J Anthropol Sci (JASS; ISSN 1827-4765)*
- Marczazan D, Meinekat SA (2022) Creating qualitative datasets in geoarchaeology: an easy-applicable description template for archaeological thin section analysis using Stoops 2003. *MethodsX* 9:101663. <https://doi.org/10.1016/j.mex.2022.101663>
- Marshall L (1976) *The !Kung of Nyae Nyae*. Harvard University Press, Cambridge
- Matthews W, French CAI, Lawrence T et al (1997) Microstratigraphic traces of site formation processes and human activities. *World Archaeol* 29:281–308
- McPherron SJP (2005) Artifact orientations and site formation processes from total station proveniences. *J Archaeol Sci* 32:1003–1014. <https://doi.org/10.1016/j.jas.2005.01.015>
- McPherron SJP (2018) Additional statistical and graphical methods for analyzing site formation processes using artifact orientations. *PLoS One* 13:e0190195. <https://doi.org/10.1371/journal.pone.0190195>
- Meignen L, Goldberg P, Bar-Yosef O (2007) The hearths at Kebara Cave and their role in site formation processes. In: Peabody Museum, Harvard University, Cambridge (ed) *The Middle and Upper Paleolithic archaeology of the Kebara Cave, Mt Carmel, Israel*. American School of Prehistoric Research, Peabody Museum, Harvard University Press (Cambridge), pp 91–122
- Mentzer SM, Romano DG, Voyatzis ME (2017) Micromorphological contributions to the study of ritual behavior at the ash altar to Zeus on Mt. Lykaion. *Greece Archaeol Anthropol Sci* 9:1017–1043. <https://doi.org/10.1007/s12520-014-0219-y>
- Mentzer SM (2017) Micro XRF. In: *Archaeological Soil and Sediment Micromorphology*. John Wiley & Sons, Ltd, Chichester, pp 431–440
- Miller CE (2015) A tale of two Swabian caves: geoarchaeological investigations at hohle fels and geißenklösterle. Kerns Verlag, Tübingen
- Miller CE, Goldberg P, Berna F (2013) Geoarchaeological investigations at Diepkloof Rock Shelter, Western Cape, South Africa. *J Archaeol Sci* 40:3432–3452. <https://doi.org/10.1016/j.jas.2013.02.014>
- Miller CE, Conard NJ, Goldberg P. et al. (2010) Dumping, sweeping and trampling: experimental micromorphological analysis of anthropogenically modified combustion features. In: Théry-Parisot, I., Chabal, L. & Costamagno, S. (eds) *The Taphonomy of Burned Organic Residues and Combustion Features in Archaeological Contexts*. Proceedings of the Round Table, Valbonne, May 27–29 2008. *P@lethnologie* 2:25–37
- Munro ND (2004) Zooarchaeological measures of hunting pressure and occupation intensity in the natufian. *Curr Anthropol* 45:S5–S34. <https://doi.org/10.1086/422084>
- Münzel SC, Conard NJ (2004) Change and continuity in subsistence during the Middle and Upper Palaeolithic in the Ach Valley of Swabia (south-west Germany). *Int J Osteoarchaeol* 14:225–243. <https://doi.org/10.1002/oa.758>
- Murray P (1980) Discard location: the ethnographic data. *Am Antiq* 45:490–502
- Nicholson RA (1993) A morphological investigation of burnt animal bone and an evaluation of its utility in archaeology. *J Archaeol Sci* 20:411–428
- Nicosia C, Stoops G (2017) *Archaeological soil and sediment micromorphology*. John Wiley & Sons
- Porraz G, Val A, Dayet L et al (2015) Bushman rock shelter (Limpopo, South Africa): a perspective from the edge of the Highveld. *South African Archaeol Bull* 70:166–179
- Reynard JP, Discamps E, Wurz S et al (2016) Occupational intensity and environmental changes during the Howiesons Poort at Klipdrift Shelter, southern Cape, South Africa. *Palaeogeogr Palaeoclimatol Palaeoecol* 449:349–364. <https://doi.org/10.1016/j.palaeo.2016.02.035>
- Riehl S, Marinova E, Deckers K et al (2015) Plant use and local vegetation patterns during the second half of the Late Pleistocene in southwestern Germany. *Archaeol Anthropol Sci* 7:151–167. <https://doi.org/10.1007/s12520-014-0182-7>
- Riek G (1934) *Die Eiszeitjägerstation am Vogelherd im Lonetal I: Die Kulturen*. Akademische Buchhandlung Franz F. Heine, Tübingen
- Riek G (1973) *Das Paläolithikum der Brillenhöhle bei Blaubeuren (Schwäbische Alb), Teil I* Verlag Müller & Gräff, Stuttgart (1973)
- Sánchez-Romero L, Benito-Calvo A, Pérez-González A, Santonja M (2016) Assessment of accumulation processes at the Middle Pleistocene site of Ambrona (Soria, Spain). Density and orientation patterns in spatial datasets derived from excavations conducted from the 1960s to the present. *PLoS One* 11:e0167595. <https://doi.org/10.1371/journal.pone.0167595>
- Schiegl S, Goldberg P, Pfretschner H-U, Conard NJ (2003) Paleolithic burnt bone horizons from the Swabian Jura: distinguishing between in situ fireplaces and dumping areas. *Geoarchaeology* 18:541–565. <https://doi.org/10.1002/gea.10080>
- Schiffer MB (1972) Archaeological context and systemic context. *Am Antiq* 37:156–165
- Schmidt RR (1912) *Die diluviale Vorzeit Deutschlands, with contributions by Koken, E., Schliz, A.* 3 vols. Schweizerbartsche Verlagsbuchhandlung, Stuttgart

- Schweingruber FH (1978) Microscopic wood anatomy. Swiss Federal Institute of Forestry Research
- Shahack-Gross R, Bar-Yosef O, Weiner S (1997) Black-coloured bones in Hayonim Cave, Israel: differentiating between burning and oxide staining. *J Archaeol Sci* 24:439–446
- Shillito LM, Matthews W, Almond MJ, Bull ID (2011) The microstratigraphy of middens: capturing daily routine in rubbish at Neolithic Catalhöyük, Turkey. *Antiquity*. <https://doi.org/10.1017/S0003598X00068460>
- Shillito LM (2015) Middens and other trash deposits. In: Bescherer Metheny K and Beaudry MC (eds) *Archaeology of Food: An Encyclopedia*. Rowman & Littlefield
- Stahlschmidt MC, Miller CE, Ligouis B et al (2015) On the evidence for human use and control of fire at Schöningen. *J Hum Evol* 89:181–201. <https://doi.org/10.1016/j.jhevol.2015.04.004>
- Starkovich BM, Elefanti P, Karkanis P, Panagopoulou E (2020) Site use and maintenance in the middle Palaeolithic at Lakonis I (Peloponnese, Greece). *J Paleolit Archaeol* 3:157–186. <https://doi.org/10.1007/s41982-018-0006-x>
- Stiner MC, Kuhn SL, Weiner S, Bar-Yosef O (1995) Differential burning, recrystallization, and fragmentation of archaeological bone. *J Archaeol Sci* 22:223–237. <https://doi.org/10.3828/bfarm.2009.3.3>
- Stoops G (2021) Guidelines for analysis and description of soil and regolith thin sections. John Wiley & Sons.
- Symes SA, Rainwater CW, Chapman EN, et al (2008) Patterned thermal destruction of human remains in a forensic setting. In: *The Analysis of Burned Human Remains*. Elsevier, pp 15–54. <https://doi.org/10.1016/B978-012372510-3.50004-6>
- Taller A, Kieselbach P, Conard NJ (2019) Reconstructing technology, mobility and land use via intra- and inter-site refits from the Gravettian of the Swabian Jura. *Archaeol Anthropol Sci* 11:4423–4435. <https://doi.org/10.1007/s12520-019-00778-8>
- Théry-Parisot I (2002) Fuel management (bone and wood) during the lower aurignacian in the Pataud rock shelter (lower Palaeolithic, Les Eyzies de Tayac, Dordogne, France). *Contribution of Experimentation J Archaeol Sci* 29:1415–1421. <https://doi.org/10.1006/jasc.2001.0781>
- Théry-Parisot I, Costamagno S, Brugal J-P, et al (2005) The use of bone as fuel during the Palaeolithic, experimental study of bone combustible properties. *Archaeol Milk Fats* 50–59
- Vallverdú J, Allué E, Bischoff JL et al (2005) Short human occupations in the Middle Palaeolithic level I of the Abric Romani rock-shelter (Capellades, Barcelona, Spain). *J Hum Evol* 48:157–174. <https://doi.org/10.1016/j.jhevol.2004.10.004>
- Varién MD, Mills BJ (1997) Accumulations research: problems and prospects for estimating site occupation span. *J Archaeol Method Theory* 4(2):141–191. <https://doi.org/10.1007/BF02428057>
- Velliky EC, Porr M, Conard NJ (2018) Ochre and pigment use at Hohle Fels cave: results of the first systematic review of ochre and ochre-related artefacts from the Upper Palaeolithic in Germany. *PLoS One* 13:e0209874. <https://doi.org/10.1371/journal.pone.0209874>
- Velliky EC, Schmidt P, Bellot-Gurlet L et al (2021) Early anthropogenic use of hematite on Aurignacian ivory personal ornaments from Hohle Fels and Vogelherd caves, Germany. *J Hum Evol* 150:102900. <https://doi.org/10.1016/j.jhevol.2020.102900>
- Villagran XS (2014) A redefinition of waste: deconstructing shell and fish mound formation among coastal groups of southern Brazil. *J Anthropol Archaeol* 36:211–227. <https://doi.org/10.1016/j.jaa.2014.10.002>
- Villagran XS, Balbo AL, Madella M et al (2011) Stratigraphic and spatial variability in shell middens: microfacies identification at the ethnohistoric site Tunel VII (Tierra del Fuego, Argentina). *Archaeol Anthropol Sci* 3:357–378. <https://doi.org/10.1007/s12520-011-0074-z>
- Villagran XS, Huisman DJ, Mentzer SM, et al (2017) Bone and other skeletal tissues. In: *Archaeological Soil and Sediment Micromorphology*. John Wiley & Sons, Ltd, Chichester, pp 9–38
- Virág A (2012) Histogenesis of the unique morphology of proboscidean ivory. *J Morphol* 273:1406–1423. <https://doi.org/10.1002/jmor.20069>
- Wadley L (2001) What is cultural modernity? A general view and a South African perspective from Rose Cottage Cave. *Camb Archaeol J* 11:201–221. <https://doi.org/10.1017/S0959774301000117>
- Wadley L, Sievers C, Bamford M et al (2011) Middle Stone Age bedding construction and settlement patterns at Sibudu, South Africa. *Science* 334:1388–1391. <https://doi.org/10.1126/science.1213317>
- Wagner E (1979) *Eiszeitjäger im Blaubeurener Tal, Führer zu Archäologischen Denkmälern in Baden-Württemberg* 6, Konrad Theiss Verlag, Stuttgart
- Waibel O 2001. *Auswertung der Knochenkohlefragmente aus den Magdalenien- und Gravettien-Schichten des Hohle Fels bei Schelkingen*. Unpublished Magister Thesis, University of Tübingen
- Will M, Bader GD, Conard NJ (2014) Characterizing the Late Pleistocene MSA lithic technology of Sibudu, KwaZulu-natal, South Africa. *Plos One* 9:e98359. <https://doi.org/10.1371/journal.pone.0098359>
- Wilson DC (1994) Identification and assessment of secondary refuse aggregates. *J Archaeol Method Theory* 1:41–68
- Wurz S (2002) Variability in the Middle Stone Age lithic sequence, 115,000–60,000 years ago at Klasies River, South Africa. *J Archaeol Sci* 29:1001–1015. <https://doi.org/10.1006/jasc.2001.0799>
- Yellen JE (1977) *Archaeological Approaches to the Present: Models for Reconstructing the Past*. Academic Press, New York

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.