Fire and Beyond: a Geoarchaeological Analysis of the Anthropogenic Features from Fumane Cave (NE Italy) and Hohle Fels (SW Germany)

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Diana Marcazzan
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1. Berichterstatter/-in:	Prof. Dr. Nicholas J. Conard
2. Berichterstatter/-in:	Prof. Dr. Christopher E. Miller
3. Berichterstatter/-in, *falls zutreffend*	Prof. Paul Goldberg

E quindi uscimmo a riveder le stelle.

Dante Alighieri, La Divina Commedia, Inferno, Canto XXXIII

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Abbreviations

UP	Upper Palaeolithic
MP	Middle Palaeolithic
BP	Before present
Kcal	Thousands of years calibrated
Kya	Thousand years ago
RF	Riparo Fumane
HF	Hohle Fels
AH	Archaeological Horizon
GH	Geological Horizon
Bef	befund (feature)
PPL	Plane-polarized light
XPL	Cross-polarized light
FTIR	Fourier Transform Infrared Spectroscopy
XRF	X-ray Fluorescence Spectroscopy
Mn	Manganese
LA	Lamb
RO	Roe deer
HO	Horse rib
HOU	Horse radio-ulna
PLS	Partial least square
PCA	Principal Component Analysis
LDA	Linear Discriminant Analysis

Abstract

Anthropogenic features provide direct evidence of human activities that took place during the occupation of a site and as such are valuable sources of information for inferring past behaviour. Their identification and interpretation is essential for archaeological research, and geoarchaeology has the potential to unravel their nature and place them into context. One of the main goals in the analysis of archaeological features is to investigate the relationship between humans and fire. A major issue in the investigation of human evolution and pyrotechnology is that fire and the ability to produce it are seen by some as one of the primary characteristics that distinguish modern humans from Neanderthals. Around this main debate, other threads open up. In fact, features like hearths can also provide insights into site maintenance, social organization, and settlement dynamics.

Here I investigate the anthropogenic features from two important Palaeolithic caves in Europe, Fumane Cave (IT) and Hohle Fels (DE). Both sites cover the transition from the Middle to Upper Palaeolithic, providing the unique opportunity to explore Neanderthal and modern human settlements. First, I analysed the thin sections using micromorphology to understand the nature of the features and their link to human activities. Second, I obtained complete information by applying complementary analyses to selected samples. Third, I executed experimental work on burning bones in a controlled environment to understand better changes in bones heated at low temperatures.

The results show a diverse set of anthropogenic features such as hearths, hearth bases, dumps, occupational horizons and laminated/trampled surfaces. Their presence reflects different activities, including combustion and site maintenance/use, carried out by humans within the site. Further, I infer fuel choice, occupation of sites and the mobility of the groups that inhabited them. Fumane Cave and Hohle Fels appear as a complex system of human behaviour based on a close relationship with the surrounding landscape. Finally, experimentation on charred bones reveals the potential of organic petrology in investigating fat-derived char and determining a range of combustion temperatures.

This dissertation shows the importance of a micro-contextual approach within archaeological research, the potential of the investigation of anthropogenic features to

reconstruct past human activities, and the need to consider them part of the cultural material. An anthropogenic feature is comparable to many other artefacts and must be treated as such to gain information on both natural processes and human behaviour.

Zusammenfassung

Anthropogene Befunde sind direkte Beweise für menschliche Aktivitäten, die während der Besiedlung einer Stätte stattgefunden haben. Sie sind wertvolle Informationsquellen, die Rückschlüsse auf vergangenes Verhalten zulassen. Ihre Identifizierung ist für die archäologische Forschung von großer Bedeutung. Die Geoarchäologie hat das Potenzial ihre Natur zu entschlüsseln und sie in einen Kontext zu bringen. Eines der Hauptziele der Befundanalyse ist, die Beziehung zwischen Feuer und Mensch zu untersuchen. Das Hauptthema dieser Arbeit ist, dass Feuer und die Fähigkeit, es zu erzeugen, oft als eines der Hauptmerkmale angesehen werden, die moderne Menschen (H. sapines) von Neandertalern unterscheiden. Neben dieser Hauptdebatteeröffnen sich weitere Themengebiete. Befunde wie Feuerstellen können Aufschluss über die Instandhaltung von Anlagen, die soziale Organisation und die Siedlungsdynamik geben.

Mit meiner Arbeit untersuche ich untersuche die anthropogenen Befunde von zwei wichtigen paläolithischen Höhlen in Europa, der Fumane-Höhle (IT) und dem Hohle Fels (DE). Beide Fundstätten decken den Übergang vom Mittel- zum Jungpaläolithikum ab und bieten die einmalige Gelegenheit, Siedlungen von Neandertalern und modernen Menschen (H. sapiens) zu untersuchen. Zunächst analysiere ich Dünnschliffe mit Hilfe der Mikromorphologie, um die Beschaffenheit der Befunde und ihre Verbindung zu menschlichen Aktivitäten zu verstehen. Zweitens erhalte ich ergänzende Informationen, indem ich ausgewählte Proben zusätzlichen Analysen unterziehe. Drittens führe ich experimentelle Arbeiten durch, bei denen ich Knochen in einer kontrollierten Umgebung verbrenne, um die Veränderungen von Knochen, die bei niedrigen Temperaturen erhitzt wurden, besser zu verstehen.

Die Ergebnisse zeigen eine Reihe anthropogener Befunde wie Feuerstellen, Basen/Untergründe von Feuerstellen, Abfallhaufen, Besiedlungshorizonte und laminierte/getrampelte Oberflächen. Ihr Vorhandensein zeigt verschiedene Aktivitäten, die von Menschen innerhalb der Stätte durchgeführt wurden, einschließlich Verbrennung sowie Instandhaltung der Fundstelle. Darüber hinaus lassen sich Rückschlüsse auf die Wahl des Brennstoffes, die Belegung der Stätten sowie die Mobilität der Gruppen ziehen

die diese bewohnten. Die Fumane-Höhle und der Hohle Fels erscheinen als ein komplexes System menschlichen Verhaltens, das auf einer engen Beziehung zur umgebenden Landschaft beruht. Schließlich zeigen die Experimente an verkohlten Knochen das Potenzial der organischen Petrologie bei der Untersuchung von aus Fett gewonnener Holzkohle und der Bestimmung einer Reihe von Verbrennungstemperaturen.

Diese Dissertation zeigt die Bedeutung eines mikrokontextuellen Ansatzes innerhalb der archäologischen Forschung, das Potenzial der Untersuchung anthropogener Befunde zur Rekonstruktion vergangener menschlicher Aktivitäten und die Notwendigkeit, sie als Teil des kulturellen Materials zu betrachten. Ein anthropogener Befund ist mit vielen anderen Artefakten vergleichbar und muss als solcher behandelt werden, um Informationen sowohl über natürliche Prozesse als auch über menschliches Verhalten zu gewinnen.

List of publications for cumulative dissertation

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Conard NJ, Janas A, **Marcazzan D**, Miller CE, Richard M, Schürch B, Tribolo C (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.

Personal Contributions

Below is the extent and significance of my personal contribution and those of my co-authors for all collaborative works in this dissertation, in accordance with § 6,2 of the Doctoral Degree Regulations of the Faculty of Science at the University of Tübingen.

I was the first and corresponding author on all the main manuscripts. I conceptualised the project ideas and conducted the micromorphological analysis, the FTIR analysis and the fabric analysis. I interpreted the result from the organic petrology and XRF analyses. Christopher Miller helped conceptualise the project idea for manuscripts. He provided editorial input and assisted in the editing of the manuscripts, including the development of some interpretations, and supervised the studies for all manuscripts provided here. Nicholas Conard provided editorial input for manuscripts 1 and 2 and supervised the studies. He is also the director of the excavation at Hohle Fels. Marco Peresani provided editorial input and assisted in writing the manuscript 1 and he is the director of excavation at Fumane Cave. Rossella Duches is the co-director of the excavation at Fumane Cave. Bertrand Ligouis performed the organic petrology analysis and provided editorial input for manuscripts 1. Susan Mentzer performed the XRF analysis.

Personal contribution and that of others involved in the burnt-bone experiment:

I conceptualized and set up the experimentation, procured the bones, processed the bones before combustion (Angel Lapaz-Blanco macerated the bones and Rudolf Walter provided the air dried horse radio-ulna), burned the bones, performed the lipid extraction (supervised by Dorothée Drucker and Nolan Ferar in the isotope laboratory at the University of Tübingen), pulverised the bones, performed the ATR and micro-FTIR analyses, performed the statistical analysis on the data and performed the interpretation of the results. Christopher E. Miller supervised the work and conceptualised the experimentation, as well as provided input for the interpretation of the data. Bertrand Ligouis cut the bones after the burning, impregnated the bones, performed the organic petrology analysis, provided input for the interpretation of the data and for the images. Susan M. Mentzer provided support along the experimentation, in particular for the FTIR and statistical analysis, as well as provided input for the interpretation of the data.

Chapter 1 Introduction

1.1 Deposits as part of the cultural material

In order to understand human behaviour, archaeologists rely on artefacts recovered during an archaeological excavation. One of the definitions of artefacts comprises all the objects used, modified, or made by people (Renfrew and Bahn 2004), such as lithics, bones, ornaments, pottery, and much more. In the recent decades, researchers have also increasingly begun to include in the concept of artefacts all the non-portable modifications (Renfrew and Bahn 2004) made by humans on the landscape and within archaeological sites. Thus, the definition now extends beyond the material object, because, just as 'natural' and 'cultural' transformation processes affect objects (Schiffer 1972), they also affect sediments. Humans act as independent agents within the environment and the deposit (Miller 2011), actively manipulating the archaeological record and contributing to its formation.

This recent approach gives new relevance to the archaeological deposits (Miller 2011), turning the deposit as active part of the cultural material and allowing geo-archaeologists to ask research questions within the anthropological sphere (Mentzer 2017). The human interactions with natural sedimentation and post-depositional processes make the archaeological layers unique (Courty et al. 1989). These assumptions become particularly relevant when talking about features. Miller (2011:94) described an anthropogenic feature as “any laterally and vertically constrained context, either depositional or erosional, that can be observed and described at a site” that has humans as the main depositional agent. A feature defines something not linked to natural factors (Courty 2001). We look at the anthropogenic feature as a bridge (Miller 2011), connecting natural and cultural processes as a direct stratigraphic link (Mallol et al. 2013) with the position of past activities and occupation surfaces. Therefore, the anthropogenic feature irrevocably transforms the archaeological deposit into the social memory of the human action (Mentzer 2017) within the site. Their finding is especially vital in Paleolithic sites, as the fewer types of traditional artefacts are generally found at sites of this age. Therefore, linking anthropogenic features with artefacts provides a more holistic interpretation of these important sites.

1.2 Anthropogenic features

The term features can be further defined and divided according to various characteristics. For example, the term “anthropogenic feature” refers to any features at an archaeological site that contain the physical evidence of human activities (Courty 2001; Miller 2011), or, when related to fire, they may take the more common name of “combustion features” (Mallol et al. 2017). A combustion feature might occur intentionally or unintentionally, encompassing a wide range of characteristics. Hearths, dumping features, sweeping or raking out features, and trampled/laminated features are among the most typical anthropogenic features found within Palaeolithic deposits (Mallol et al. 2017).

A hearth (i. e. combustion structure) is a feature containing physical by-products of fire (Mallol et al. 2017) found in their original position of burning. They typically appear as a sedimentary sequence of two or three horizontal layers (Meignen et al. 2007), often with sharp and abrupt contacts. The typical sequence preserves burnt substrate at the base overlain by charred organic matter from burnt residues, and an ash micro-unit on the top (Meignen et al. 2007).

The characteristics of this sequence depend on different factors (Canti and Linford 2000; Sievers and Wadley 2008), from the interaction of the substrate (usually sediment) and heat, the fuel source, the source of ignition (Mentzer 2014), and differences in time and temperature of the combustion event (Canti and Linford 2000; Homsey and Sherwood 2010; Aldeias et al. 2016; Liedgren et al. 2017; Ferro-Vázquez et al. 2022). The original composition of the substrate, such as porosity and water content, and following post-depositional processes determine the thickness of the burnt surface (Clauser et al. 1995; Mentzer 2014; Ferro-Vázquez et al. 2022). High content of charred and organic material produces a dark brown or black sediment coloration (Mallol et al. 2013), whereas the red colour often associated with heating events (Canti and Linford 2000) derives from a rubification process due to the ferric oxide enrichment of some substrates (Röpke and Dietl 2017).

However, archaeologists must be careful as the rubified colour can be caused by mechanisms other than combustion (Taylor and Schwertmann 1974; Torrent et al. 1983) and human activities can also enrich the sediment with haematite (Wadley 2010; Henshilwood et al. 2014). Thus, the identification of an in-place combustion structure cannot entirely be based on the presence of this rubified layer as it may be due to other factors or even entirely absent from the structure (Mentzer 2014).

Analysis of the charcoal and ash layers is therefore a fundamental tool to evaluate (Mentzer 2014; Mallol et al. 2017) the presence of a hearth and to understand its characteristics. For example, the amount of fuel can affect the thickness of the burnt residue while the type of fuel sources determines its composition and structure. The black layer (Mallol et al. 2013) can provide us with information on the type of fuel used. It can consist of fine sediment enriched with partially combusted organic material (Mallol et al. 2007; Goldberg et al. 2012; Mallol et al. 2013) and charcoal, but also of burnt bone fragments (Schiegl et al. 2003; Karkanas and Goldberg 2010) and combusted animal fat (Miller 2015). Whereas the ash layer results from the partial combustion of plant tissues (Mentzer 2014; Mallol et al. 2017; Karkanas 2021) and may also include phytoliths or other microscopic plant remains that may be used to reconstruct fuel selection strategies, along with the landscape or past site activities (Goldberg et al. 2009; Wroth et al. 2019).

The analysis of the burnt components can be useful to infer the use of a hearth, such as open hearth (Mallol et al. 2017), sealing campfire (Villagran et al. 2013), or domestic ovens (Matthews 2010) among others. Although the types of hearths are many (Mentzer 2014), in Palaeolithic sites the most common is the open hearth (Mallol et al. 2017). The open hearth often appears as a discrete feature (Meignen et al. 2007; Berna and Goldberg 2007; Miller et al. 2010; Wadley et al. 2011) or as sequences of alternating black, ash, and rubified layers (Meignen et al. 2007; Berna and Goldberg 2007; Miller et al. 2010; Wadley et al. 2011), created by repeated combustion events in the same place (Meignen et al. 2007; Vallverdú et al. 2012).

Depositional and post-depositional processes can heavily affect the preservation of a hearth, making the identification problematic (Goldberg et al. 2017). Along with geogenic and biogenic processes, human actions (Mallol et al. 2017) can also impact the characteristics of a hearth, including processes like dumping, raking out, sweeping, and trampling.

Dumping occurs when humans remove waste material from the main occupation area and dump it somewhere else (Brönnimann et al. 2020), usually in the periphery of the occupation area (Meignen et al. 2007). When the discarded material is predominantly burnt, the dumping is likely related to cleaning and maintaining of a hearth. Evidence of dumping is found in many hunter-gather site such as Kebara Cave (Meignen et al. 2007), Üçağızlı Cave (Kuhn et al. 2009; Baykara et al. 2015), Lakonis I (Starkovich et al. 2020), Hohle Fels (Schiegl et al. 2003), Sibudu Cave (Goldberg et al. 2009), Diepkloof (Miller et al. 2013), and Bushman Rockshelter (Porraz et al. 2015). The action of dumping create features with a wide range of shapes and sizes often depending on the pre-existing surface's morphology (Karkanas and Goldberg 2018). The sediment is generally poorly sorted (Miller et al. 2010) and might include rolling pedofeatures, such as coatings around the coarse fraction, due to the rapid movement of the dumped formation (Mallol et al. 2017). The components preserve a chaotic organization, having different sizes and with characteristics created through exposure to different temperatures (Schiegl et al. 2003). They show little to no evidence of compaction or in situ snapping (Miller et al. 2010). Because of the removal, dumped features do not preserve a burned substrate at the bottom (Miller et al. 2010). Thus, the distance (Karkanas et al. 2015) of a dumped deposit from a burnt substrate (Mallol et al. 2017) might help to distinguish it from processes like sweeping and raking-out.

These minor processes are part of regular maintenance activities (Karkanas and Goldberg 2018) carried out either manually or with implements (e.g., a rake or broom). The purpose of sweeping or raking an area is to remove some of the material (Meignen et al. 2007), such as small chunks of unburnt fuel from a previously used hearth from the occupation area to the side and to prepare the surface for its next use (Karkanas et al. 2015). Raking generally removes the larger fragments, both burnt and unburnt, into the area around the hearth, leaving a larger percentage of smaller fragments in the hearth (Meignen et al. 2007). The material appears spread heterogeneously (Meignen et al. 2007), due to the incremental and steady movement that drags, turns, and mixes the particles (Meignen et al. 2007). Particles may show a roughly horizontal orientation (Meignen et al. 2007) after raking, such as horizontal charcoal stringers (Homsey and Capo 2006). On the other hand, the swept material appears more homogeneous (Miller et al. 2010), likely because the process better sorts the material. For example, fine components are removed from the centre of the hearth with rapid sweeping movements, while coarser components are pushed away. Finally, it appears that the sweeping process affects both the material swept away and the remaining surface area (Karkanas and Goldberg 2018), as coarse material cannot be completely removed.

Finally, trampling is also a common process within Palaeolithic sites. Often associated with the transformation and arrangement of the substrate (Rentzel et al. 2017), trampling is a sign of human, but also animal, traffic within the site. Identified in many different archaeological settings, trampling is one of the main formation processes, and at the same time, a post-depositional alteration produced by human activities (Banerjea et al. 2015; Karkanas and Goldberg 2018), and can be indicative of the intensity of the use of space at a site. The typical modifications attributed to the trampling process (Miller 2017; Rentzel et al. 2017) are microstructural changes to the substrate. In particular, the compaction causes a massive microstructure, made by the alternation of different lenses of sediment compressed during or after the deposition. This compression has a clear effect on the coarse material, visible in the horizontal orientation and parallel distribution of the components (Miller et al. 2010), and to the greater incidence of breakage (Starkovich et al. 2020). It is also possible to see a development of laminated bedding structures, arranged in an alternating sequence of several layers, described as trampled occupation deposit (Banerjea et al. 2015) and identified as the accumulation of various mineral and organic components during the occupation (Rentzel et al. 2017).

1.3 Anthropogenic features and human behaviour

The occurrence of anthropogenic features is now widely accepted as direct proof of past human activities carried out during the occupation of a site (Mallol et al. 2017) and their discovery provides a wealth of information. The application of principles and techniques typical of geoarchaeology into the features' analysis enables the integration of theoretical (Gowlett 2006; Karkanas et al. 2007; Sandgathe et al. 2011; Roebroeks and Villa 2011; Fernández Peris et al. 2012; Shahack-Gross et al. 2014; Stahlschmidt et al. 2015; Sorensen 2017) and methodological (Stiner et al. 1995; Miller et al. 2010; Thompson et al. 2013; Mallol et al. 2013; Karkanas 2021) research questions (Mentzer 2017).

A geo-archaeological investigation of the combustion features, in particular hearths, tells us about the relationship between humans and fire (Leierer et al. 2020). It shows us how this relationship evolved, from a first opportunistic use of natural fire (Clark and Harris

1985; Pruetz and LaDuke 2010), through the control of fire (Clark and Harris 1985; Gowlett and Wrangham 2013), finally arriving at the actual production of the fire (Weiner and Floss 2004; Sorensen et al. 2014). The moment when human groups switched from exploiting natural fire to the ability to produce fire is considered a significant turning point. However, it is not always easy to identify the difference between these two types of fire use within archaeological deposits. This difficulty has led to heated debate regarding this transition (Karkanas et al. 2007; Sandgathe et al. 2011; Roebroeks and Villa 2011; Fernández Peris et al. 2012; Sorensen 2017), especially in the European context and in the broader Neandertal-Sapiens debate.

In Europe, the control and use of fire only became common from the second half of the Middle Pleistocene, around 300-400 ka (Roebroeks and Villa 2011). A first convincing evidence of controlled and repeated use of fire comes from Qesem Cave (Israel), in the Late Lower Palaeolithic (Karkanas et al. 2007; Shahack-Gross et al. 2014). Further, we have strong fire evidence from numerous sites such as Abric Romani and Vanguard Cave (Macphail and Goldberg 2000; Courty et al. 2012) in Spain, Pech de l'Azé IV and Roc de Marsal (Dibble et al. 2009; Goldberg and Berna 2010; Goldberg et al. 2012) in France, Fumane Cave (Marcazzan et al. 2022) in Italy and many others (Mentzer 2014). It is also well established through the existence of Mousterian fire making tools from multiple Middle Palaeolithic (MP) archaeological sites in France dating to the Last Glacial (Rots et al. 2011; Sorensen et al. 2014; Heyes et al. 2016).

Understanding how to control fire is considered by many to be the key to the behavioral evolution of hominins (Mentzer 2017), as it brought significant behavioural and cultural changes. Among the most common changes are anatomical modifications (Wrangham et al. 1999) deriving from a change in subsistence strategies (Goudsblom 1986; Brown et al. 2009; Mallol et al. 2017) as well as technological innovations (Aranguren et al. 2018; Schmidt et al. 2019), which might have helped with the colonization of challenging environment (Wrangham et al. 1999; Rolland 2004; Gowlett 2006; Preece et al. 2006; Stahlschmidt et al. 2015). Perhaps more importantly, fire control and use led to social changes (Gowlett 2006; Wrangham 2007, 2017; Twomey 2013; Kuhn and Stiner 2019), either due to the distribution of tasks within the group (e.g., gathering, accumulation, cooking, defence) or simply due to the socialising effect of gathering around campfires at night (Pyne 1995).

Along with human-fire relationship, the investigation of the anthropogenic features may provide us with information on landscapes management (Eckmeier et al. 2007; Roos 2008; Conedera et al. 2009; Bowman et al. 2011), site maintenance activities (Goldberg et al. 2009; Wadley et al. 2011), and intensity/length of occupation (Vallverdú et al. 2012; Miller et al. 2013; Karkanas et al. 2015; Haaland et al. 2021a).

Landscape management can be seen, in a very broad sense, as linked to the so called "fire regimes" (Pausas and Keeley 2009). Bowman (2011) defines a fire regime as a "spatially variable template of fire intensity, severity, type, frequency, spatial scale and seasonality, within which biotas have co-evolved". Within the fire activity on the landscape, temporal or spatial changes often coincide in space and time with changes in human history (Bowman et al. 2011). This connection is seen frequently during the colonization of new environments (Bond and Dickinson 2004; Miller et al. 2005; McWethy et al. 2010). The human-landscape-fire relationship (Bellomo 1993; Buenger 2003; Bowman et al. 2011; Gowlett 2016), is resilient from the beginning, and its effect grows stronger as human history progresses.

Humans influence the landscape, and vice versa, in many ways (Bowman et al. 2011). We see an example at the site level by looking at the fuel. The change in fuel types and availability can modify the structure and continuity of the lighting of fires. A small glimpse of this interweaving of relationships can also occur in prehistory and is understood via the material that humans used to light the campfire (Miller 2015). The selection of fuel in the hunter and gatherer groups is strongly correlated with the sources available in the landscape and, thus, it strictly depends to paleoenvironmental aspects (e.g., the type of vegetation cover surrounding a site) (Aldeias 2017). However, it is also true that human behaviour and choice have strong implications for the collection of material for fuel, including selection criteria, effort, and collection costs (March 1992; Théry-Parisot 2002a; Villa et al. 2002; Théry-Parisot 2002b; Théry-Parisot and Henry 2012; Henry 2017). On the other hand, the fuel selection also depends on the fuel performance with regard to the functions of the hearth (Théry-Parisot 2002a; Villa et al. 2002; Théry-Parisot 2002b; Théry-Parisot and Henry 2012; Henry and Théry-Parisot 2014).

Linked to the landscape and the site itself, the study of the anthropogenic features add to our understanding of the type of maintenance activities that humans carried out (Goldberg et al. 2009; Miller et al. 2010; Mallol et al. 2017). For instance, the periodic burning of anthropogenic ground surface coverings (bedding) (Goldberg et al. 2009) is a well-known maintenance activity. Goldberg et al. (2009) identified this technique during the Middle Stone Age in Sibudu Cave (South Africa), as a possible means of ridding their domestic space of wastes and insects (Wadley et al. 2011). This technique is used more frequently in later periods like the Neolithic (in Fumier deposits) when caves and rock shelters were used as stables for animals and periodic burning of dung and fodder was used to revitalize the areas (Angelucci et al. 2009).

Understanding what type of maintenance activities occurred and recognizing their location within a site helps researchers to understand the human organization of space and to infer the length of the site occupation. The idea that the hearth is the natural focal point around which many activities take place is well established (Binford 1978). However, a hearth only represents one step within the potential life-history of an anthropogenic/combustion feature (Bentsen 2014). After burning, people can reuse the hearth or abandon it. If the feature is reused, they can also clean the hearth by sweeping or raking-out material, or completely remove the leftover residues and dump of them elsewhere. These actions are important aspects of the range of activities associated with fire-related behaviours (Miller et al. 2010) and provide insights into a site's spatial organization (Goldberg et al. 2009; Miller et al. 2013), as well as degrees of mobility (Karkanas et al. 2015; Haaland et al. 2021a).

For example, the designation of a particular location for waste material highlights the tendency for structuring the occupation area at hunter-gatherer sites (Goldberg et al. 2009; Miller et al. 2013; Karkanas et al. 2015; Haaland et al. 2021a). Ethnoarchaeological studies of hunter-gatherer groups (Marshall 1976; Yellen 1977; Murray 1980; Brooks and Yellen 1987; Binford 1996). support these archaeological assumptions. They suggest a certain degree of connection between how group's structure and maintain their campsites and how they move about on the landscape. Murray (1980) shows sedentary and semi-sedentary groups generally have designated areas for waste material in a distinct location, far from living space. Yellen (1977) observed that few formal divisions occur between subsistence and manufacturing processing areas when the occupation lasts for shorter periods. However, when the occupation time lengthened , fuel remains, and other refuse were disposed of in a designated area. In particular, Brooks and Yellen (1987) noticed that in !Kung camps waste material remained at its production location during short occupations, but it was dumped outside of the camp during longer-term occupation.

Methodologically speaking, the analysis of anthropogenic material (including artefacts and features) represents an essential step in expanding our knowledge and insight into the nature of the features and human behaviour. For this reason, many laboratories have carried out intensive research on materials and sediments in recent decades. This research has taken place both through experimental work and on archaeological assemblages. In addition to the work already mentioned on burnt sediments, there is also a great deal of specific research on other combustion products and detailed reviews of these types of analyses can be found in Mentzer 2017, Nicosia and Stoops 2017, and Karkanas 2021. As an example of how these materials may be analysed, here I summarise the main burnt components we found during the analysis of Fumane Cave and Hohle Fels, such as ash, charcoal, bone, and char.

Ash results from burning dry plant material (Canti 2003; Karkanas 2021). The typical colour is whitish (Canti 2003) because of the siliceous and calcitic contents (Mentzer 2014). This colouration may differ from white when the charcoal content increase (Mentzer 2014) or because of different burning temperatures (Wattez 1990). Yellow or brown ashes derive from moderate intensity heating, while grey or white ashes derive from high intensity burning (Wattez 1990; Mentzer 2014). Under the microscope, ash appears as calcite (CaCO3) pseudomorphs originating from the decomposition through heating of calcium oxalate crystals, which are the biogenic part of many woody species (Canti 2003; Shahack-Gross and Ayalon 2013; Canti and Brochier 2017). These calcite pseudomorphs have a rhombic, triangular shape, though this shape may appear different during micromorphological analysis depending on the thin section cut (Mentzer 2014; Karkanas 2021). There are also rare cases where the shape of the oxalate pseudomorphs may vary due to the plant species in which they originate (Meinekat et al. 2022). Unfortunately, chemical alteration frequently occurs on ashes (Weiner et al. 1993, 2002; Schiegl et al. 1996; Karkanas et al. 2000; Karkanas 2010; Miller et al. 2016). Chemical alteration is recognizable through partial dissolution and recrystallization of the rhombs, and the ash will convert into apatite or other phosphates in some cases. For example, when bat guano or bones are present (Karkanas et al. 2002; Shahack-Gross et al. 2004; Miller 2015), the ash may lose its birefringence (Canti and Brochier 2017) and assume a yellowish coloration due to interactions with the chemicals present in the other materials.

Charcoal fragments are often visible to the naked eye (Mentzer 2014) and are one of the main proxies used to identify a burning event during an archaeological excavation. In thin sections, charcoal appears as opaque fragments in both plane and crossed polarized light

(Canti 2017), ranging from very fine sand to fine gravel. Sometimes the typical woody plant structure is visible, making it possible to distinguish between ring-porous hardwood, diffuse-porous hardwood and softwood (Schweingruber 1978; Canti 2017). In some cases, studies on the preservation of charcoal and the formation temperatures offer clues to the use of fire (Braadbaart and Poole 2008; Braadbaart et al. 2012). For example, it is possible to identify the charcoal types through the use of reflected light (Goldberg et al. 2009; Ligouis 2017; Marcazzan et al. 2022) and differentiate between grass and woody tissues. Further, organic petrology is an essential tool to distinguish decayed plant material from charcoal, which can often be confused with other microscopic techniques (Braadbaart and Poole 2008), or to identify the charcoal's degree of burning. Such information is useful with a view towards understanding fuel procurement (Théry-Parisot et al. 2005; Théry-Parisot and Texier 2006; Théry-Parisot et al. 2010a) and the duration of occupation.

Along with plant remains, animal-derived products are important finds often connected to the anthropogenic features and fire events. One such product is fat-derived char (Mentzer 2014; Mallol et al. 2017), which often appears in association with burnt bones (Schiegl et al. 2003). It appears black and opaque in PPL, without a cellular structure and with vesicles. These characteristics and a ‘drop like’ morphology indicate that this material was a fluid that subsequently cooled (Mallol et al. 2017). Char derives from the combustion of flesh and fat and its presence may indicate a specific function of the fire (Mentzer 2014) and specific fuel choices, such as the use of a fire for roasting meat or to dispose of waste bones.

The presence of bones within a combustion feature is interesting as they are often identified as fuel and are, therefore, intensively studied. Both in the field and in thin section analysis, the colour of a bone is used as an indicator of burning temperature (Stiner et al. 1995; Hanson and Cain 2007; Villagran et al. 2017a): pale yellow for low temperatures, black-dark brown for medium temperatures, and white to blueish for high temperatures. It is worth mentioning that there is a certain degree of variation in the presentation of these colours between bones of different animal species (Nicholson 1993) and between types of bones with diverse fat content (Symes et al. 2008). Aside from the colour change, other microscopic manifestations occur within the bone due to combustion, including fracture patterns, mechanical strength (Thompson et al. 2009), and crystallinity (Ellingham et al. 2015). The mineral fraction of bone also becomes altered by heat, especially after 30 minutes (Thompson et al. 2009), providing a means for identifying and tracking heating in the past (Villagrain et al., 2017). In fact, many other methods have been applied on bones in order to understand the degree of burning like x-ray fluorescence (XRF) (Kalsbeek and Richter 2006), Fourier-transform infra-red (FTIR) spectroscopy (Stiner et al. 1995; Thompson et al. 2009, 2011, 2013; van Hoesel et al. 2019), Raman spectroscopy, x-ray diffraction (XRD) (Piga et al. 2008, 2009; Galeano and García-Lorenzo 2014), organic petrology (Clark and Ligouis 2010), autofluorescence (Lambrecht and Mallol 2020), and many others.

However, combustion is not the only human process that can affect bones. Trampling (Miller et al. 2010; Rentzel 2017), for example, can create distinctive fractures (Villagran et al. 2017) identifiable in thin sections. Indeed, due to trampling, bones appear broken (or shattered) in situ and slightly accommodated (i. e. “shapes that can be fitted or meshed together by an imaginary movement or translation that brings the opposing faces together” from Stoops 2021:73). By recognising these mechanical fractures (Villagran et al. 2017), we can provide meaningful data on intentional or unintentional human practices. Specifically, the finding of trampling evidence may be the only evidence to determine whether or not parts of the site were used by human groups.

1.4 Objectives of Study

This dissertation centres on the investigation of the anthropogenic features from the Middle (MP) through the Upper Palaeolithic (UP) in two caves, Fumane Cave in Italy and Hohle Fels in Germany. The MP and UP is a key time period for debates focused on fire use and fire making (Gowlett 2006; Karkanas et al. 2007; Roebroeks and Villa 2011; Sandgathe et al. 2011a; 2011b; Fernández Peris et al. 2012; Shahack-Gross et al. 2014; Stahlschmidt et al. 2015; Sorensen 2017) and research has primarily focused on identifying early evidence for fire use due to its significance for human evolution (Chazan 2017; Sandgathe 2017; Stahlschmidt et al. 2015). The issue of fire is so vociferously debate as one side sees fire and the capability of producing fire as a primary trait that distinguished Sapiens from Neanderthal (Sandgathe et al., 2011; Sorensen 2017). Thus, the investigation of archaeological deposits that includes features from MP and UP is a unique opportunity to analyse Neandertal material, deposits from periods where overlap may have occurred, and material related to solely *Homo* sapiens. However, as mentioned earlier, analysing the anthropogenic features from an archaeological deposit is not only investigating the fire- human relationship. It also means reaching for a deep understanding of the deposit itself and the role that humans played during the site occupation. The focus on fire and fire- related features stems from the intrinsic value that such features take on, functioning as both behavioral and paleoenvironmental archives (Stahlschmidt et al., 2020). Despite this focus, the identification of fire evidence is not always easy or straight forward. Many researchers have noted that visual observations or identification on the macro-scale alone are not reliable on their own. Therefore, they should be confirmed using a micro-contextual investigation through laboratory analysis (Mentzer 2017).

I approach my research into fire at Fumane Cave and Hohle Fels in a series of interrelated steps: first, I perform a micromorphological analysis on the thin section of both sites; second, I conduct complementary analysis on selected features in order to obtain complete information on different fuel choices, the degree of burning, and scale of natural reworking; third, I perform an experimental work on burning bones in a controlled environment to better understand the chemical nature of bones heated at low temperatures.

The main objectives of this dissertations are to:

- Investigate the nature of the anthropogenic features starting from the data collected during the excavation through the application of the concepts and methods typical of geoarchaeology.
- Apply a complementary, multi-analytical approach to obtain better information on the degree of burning, fuel choices, and degree of natural reworking.
    - Understand the possible fuel selection strategies through the investigation of experimental burnt bones.
- Identify any diachronic pattern or change in terms of features, human behaviour, and intensity of occupation by Neanderthal and Sapiens groups within both sites.

Chapter 2 Archaeological background

2.1 Fumane Cave: archaeological background

In 1884, Stefano De Stefano first reported the location of Grotta di Fumane, which was at the time completely obstructed by a landslide. However, it was not until 1964 that a preliminary excavation began under the direction of Prof. A. Pasa, after Giovanni Solinas rediscovered the cavity. This first investigation, though, soon came to an end, and the site was abandoned and plundered by clandestine excavations. Finally, in 1982 M. Cremaschi and A. Sartorelli began a stratigraphic examination (Cremaschi et al. 1986), thanks to the Soprintendenza Archeologica del Veneto and the Museo di Storia Naturale di Verona. This preliminary analysis then turned into a systematic excavation in 1988, which continues to this day, first under the direction of Alberto Broglio (University of Ferrara) and Mauro Cremaschi (University of Milan) and today of Marco Peresani (University of Ferrara).

Grotta di Fumane (Fig 1) is a karstic cave located at the foot of a fan-shaped plateau in the western part of Veneto Pre-Alps (north-eastern Italy situated) at 350 m above the sea level (asl). Due to its location, the cave is in strategic position for the access to different types of raw material and environments, on the boundary between the alpine meadow and coniferous forest, (Romandini et al. 2014). Belonging to a complex karstic system, Fumane Cave has a large entrance area and three cavities. Its archaeological record preserves a remarkable stratigraphic sequence (12 m) covering the shift from the MP to the UP (Fig 2).

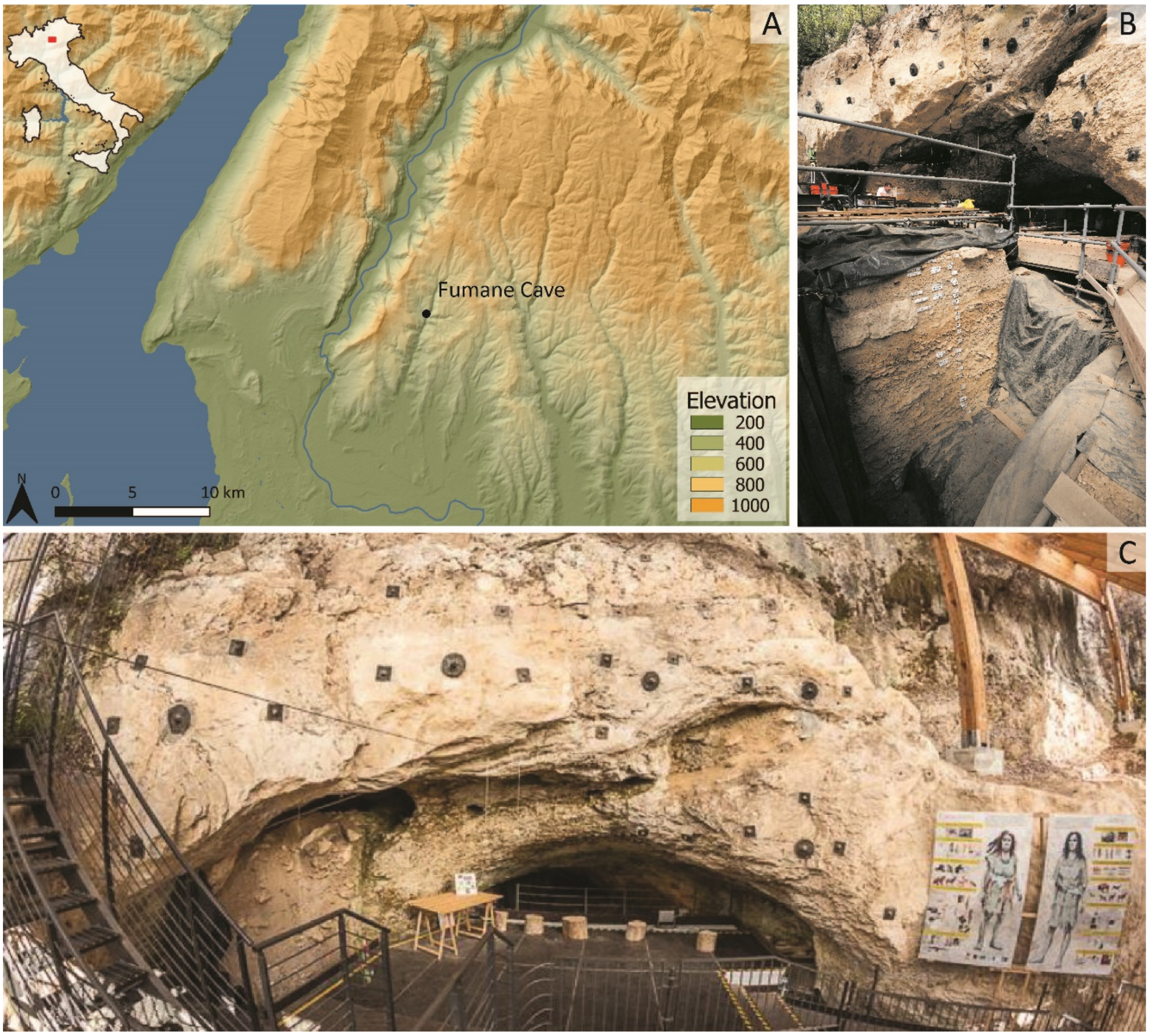

Fig 1: (A) Map showing the location of Fumane Cave. (B) photo of the lower part of the stratigraphy. (C) photo of the overview of the atrial area of the cave. Technical notes: Coordinate system: EPSG:3003 - Monte Mario/Italy zone 1 - Projected; Digital Elevation Model from U.S. Geological Survey; Waterbody from Geoportale Nazionale (http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/wfs/Bacini_idrografici.map and http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/wfs/Aste_fluviali.map).

2.1.1 Archaeological assemblages

The late MP deposits that have been the focus of the most intensive investigations consist of several layers (A11, A10, A9, A5-A6, A4; A7 does not record human frequentation), including some already excavated over laterally extensive areas on the main cave surface. A10 and A11are currently under excavation. Dating from 49±7 ka BP to 44.9-42.0 ky cal BP (Douka et al. 2014; Peresani et al. 2017), the late MP is characterized by the repeated appearance and abandonment of lithic knapping methods and various faunal markers (Peresani 2012). The lithic production shows an alternation between and, in some layers, the coexistence of Discoid and Levallois industries. The assemblage from A9 displays technological variability from the Discoid reduction concept (Delpiano et al. 2018), whereas the A11, A6-A5, and A4 layers display Levallois characteristics. Currently, a coexistence of the two methods (Peresani et al. 2017) characterizes A10. The Mousterian macrofaunal assemblage is mainly the result of human activity, with a small contribution from large carnivores. The bone fragments show underly carcass processing, raw material exploitation (Jéquier et al. 2018; Martellotta et al. 2020) and burning. The main prey animals are red deer, roe deer, ibex, chamois, and giant deer among the ungulates, with this selection probably being dictated by their availability near the site (Fiore et al. 2004, 2016; Peresani et al. 2011b, a, 2017; Romandini et al. 2014, 2016). Considering the entire faunal spectrum (including carnivores and birds), the analysis shows a varied ecological context in cool-temperate climate conditions with both wooded areas and open spaces. The interpretation of the local ecology as reconstructed from micromammals (López-García et al. 2015) and macromammals analysis also fits with the analysis of charcoal that shows a prevalence of larch in A9, A5, A5+A6, and A6 layers (Peresani et al. 2011a; Basile et al. 2014). However, these conditions seem to progressively change and turn dryer and colder from layer A3 (Uluzzian) (Tagliacozzo et al. 2013; Romandini et al. 2020).

The lithic and faunal evidence in layer A3, dated to 45.0-42.0 ky cal BP (Douka et al. 2014), is interpreted as representing a transitional complex - the Uluzzian - when the site was used less intensively, and likely served as a camp for prey exploitation and lithic production rather than for longer-term residential occupation (Peresani et al. 2016). The Uluzzian complex presents a lithic assemblage distinguished by the presence of flakes, among which the main varieties of tools are scrapers, splintered pieces, and backed flakes, demonstrating a possible break from the previous technological tradition (Peresani et al., 2016). The analysis of the faunal remains from A3 suggests again the exploitation of red deer and ibex, as well as the presence of birds and carnivores from the cave surroundings (Tagliacozzo et al., 2013). Although still characterised by a large number of archaeological remains, the Uluzzian shows a decrease in anthropic material compared to the earlier deposits (Peresani et al., 2016). This trend connected to deeper micromorphological analyses (Kehl et al., in prep), showing no changes in sedimentation rate, leading to the assumption of a decrease in human presence at the site.

The upper part of the stratigraphic sequence (A1-A2 and D units) includes UP occupations dated from 41.2–40.4 ky cal BP (Higham et al. 2009; Higham 2011). This portion of the sequence begins with the appearance of the Protoaurignacian complex in layers A1 and

A2, followed by the late Protoaurignacian within the D macro-unit. The faunal assemblage suggests that the site remained a strategic point for hunting as the species found in the Upper Palaeolithic layers come from the alpine grassland steppe (at that time extended from about 300-400 meters upwards) and the coniferous forest that occupied the surrounding hills (Bertola et al. 2009). Analysis of the faunal remains demonstrates a hunting strategy mainly focused on young and old individuals and shows a preponderance of species adapted to cooler and dryer conditions compared to the underlying layers (Bertola et al., 2009). The lithic industry relies on a laminar method for the production of blades and bladelets. The tool categories are represented by end-scrapers, blades, and burins (Falcucci et al. 2017). As documented in the underlying layers, the supply of raw material is always local, and humans introduced it into the cave before processing. The Protoaurignacian is also remarkable for the production of bone and antler tools, such as awls and perforators (Bertola et al., 2013). Organic points have been found in the D levels, including some ascribable to split-based point typology. Finally, ornamental objects represent a crucial cultural theme within the Fumane deposit. Within the artifact assemblage there are hundreds of perforated shells (mostly marine shells), four incisors of deer artificially grooved to facilitate suspension, and fragments of limestone from the vault painted with red ochre, including an anthropomorphic figure among the represented motifs (Bertola et al. 2009; Peresani et al. 2019).

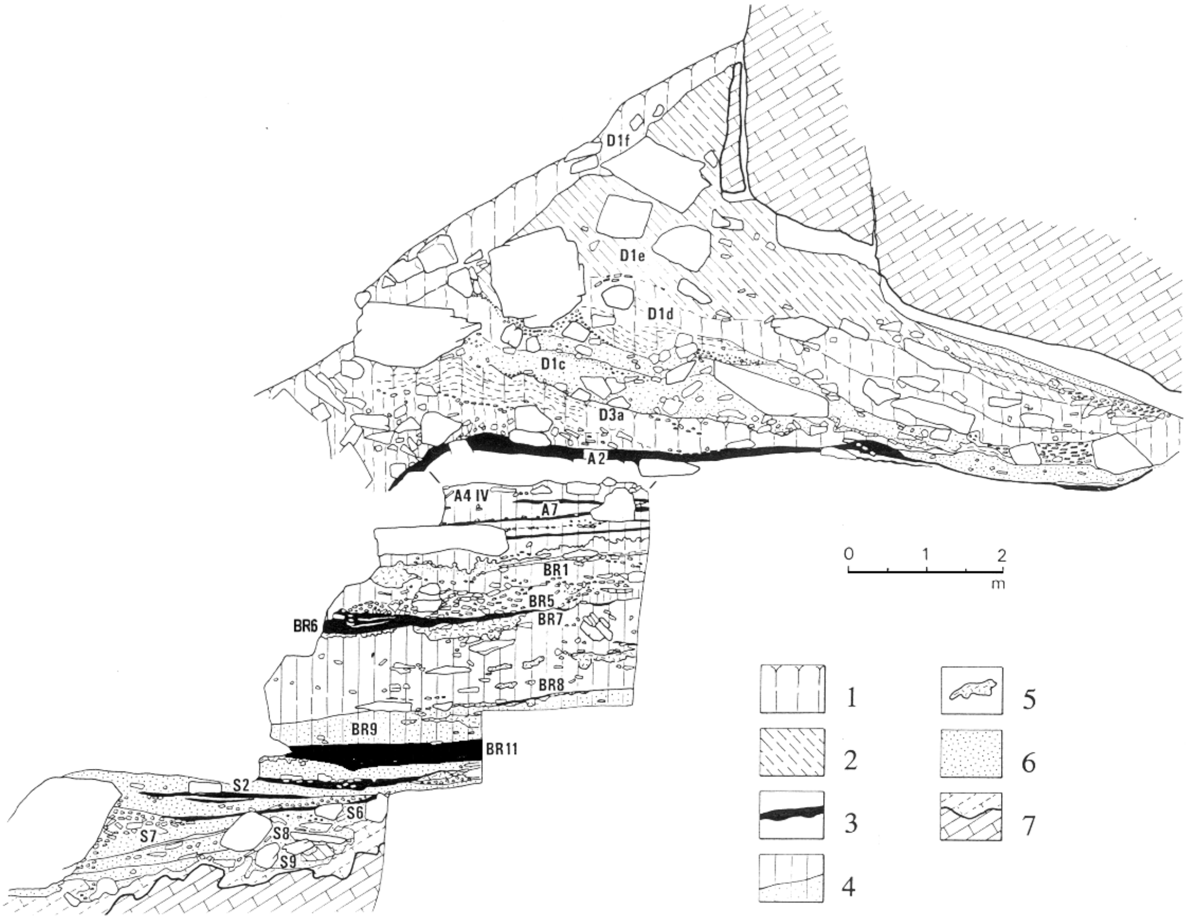

Fig. 2: Stratigraphic section showing the layers under analysis. Late Mousterian (A11-A4), Uluzzian (A3) and Early Aurignacian (A2) (by M. Cremaschi & M. Peresani).

2.1.2 Previous geoarchaeological works

Previous geoarchaeological studies carried out at Fumane focus mainly on the geogenic formation processes of the site (Cremaschi et al. 2005; Peresani et al. 2011a). The initial study by M. Cremaschi investigated the entire stratigraphic sequence and provided preliminary data on the depositional and post-depositional processes acting within the cave (Cremaschi et al. 2005). He subdivided the sequence based on lithological, pedological and cultural characteristics. The stratigraphy is divided into four macro-units S (sabbie), BR (brecce), A (antropico) and D (debrìs) (Cremaschi et al. 2005; Abu Zeid et al. 2019). Macro-unit S primarily consists of dolomitic sands arranged in a planar stratification, which lie directly on the weathered bedrock. Macro-unit BR, in contrast, is characterized by layers rich in frost-shattered rocks and layers with a higher proportion of fine fraction (aeolian silt and dolomitic sand). Cremaschi et al. (2005) interpreted the alternation between the fine and coarse layers as a result of significant changes in climatic conditions (Cremaschi et al., 2005; Abu Zeid et al., 2019). Inside the BR macro unit, there are two darker, anthropogenic units (BR11 and BR6). Macro-unit A is the subject of extensive excavation and takes its name from the intense and repeated human occupation (Peresani et al. 2011a; Peresani 2012). Characterized by sub-horizontal layers, it is mainly composed of aeolian? dust, dolomitic sand, and frost shattered stones (Cremaschi et al., 2005). Finally, macro-unit D is the result of the vault collapse. The main components are large boulders and a fine sand matrix, accumulated to the point of sealing the cavity.

The work of Peresani et al. (2011a) focused on layer A6 (Mousterian), providing insight into the geogenic and anthropogenic processes within this single layer. In A6 and A5, the coarse fraction consists mainly of limestone éboulis fragments and dolomite sand from the disintegration and dissolution of the vault of the cave. Along with these allochthonous components, there are mica and quartz grains, deposited inside the cave by aeolian transport. However, the main result of this work highlighted the anthropogenic richness of the deposit.

2.2 Hohle Fels: archaeological background

The first paleontological excavations at Hohle Fels (Fig. 3) began in the late 19th century under the supervision of Oscar Fraas and Theodor Hartmann (Fraas 1872; Riek 1934; Hahn et al. 1978). However, it was not until 1973 that Joachim Hahn and colleagues (Hahn 1977) started systematic archaeological excavations at Geißenklösterle and Hohle Fels. Nicholas Conard and Hans-Peter Ueperman continued Riek's work after his death in 1997 (Conard and Uerpmann 2000) To date, excavations at Hohle Fels are still ongoing under the direction of Nicholas Conard (University of Tübingen) (Miller 2015). The research in recent decades has concentrated on the small apse before the great hall, with the aim of exploring the UP and MP layers (Conard et al. 2021). Thus, the last few years of excavations (Conard et al. 2021) have made a particularly important contribution to increasing the knowledge of the Palaeolithic in the Swabian Alb and beyond (Conard et al. 2006). The Swabian Alb (Schwäbische Alb in German) is a plateau in southwestern Germany (Baden-Württemberg) bordering the Danube River. The plateau retains typical geomorphic features of a karst landscape (Geyer and Gwinner 1991; Goldberg et al. 2003; Schiegl et al. 2003; Miller 2015). The region (Goldberg et al. 2003), and in particular the Ach and Lone Valleys, is a key area for studying the transition from the MP to the UP

(Conard 2003, 2011; Conard and Bolus 2003) and the development of cultural and symbolic behaviour (Conard 2003, 2011; Velliky et al. 2018). For this reason, both the Ach and Lone Valleys and their caves have recently been declared UNESCO World Heritage Sites because of the exceptional nature of their deposits. Among the numerous caves, Hohle Fels Cave is one of the largest. It lies approximately at 534 metres asl within upper Jurassic (Malm) limestone bedrock (Goldberg et al. 2003).

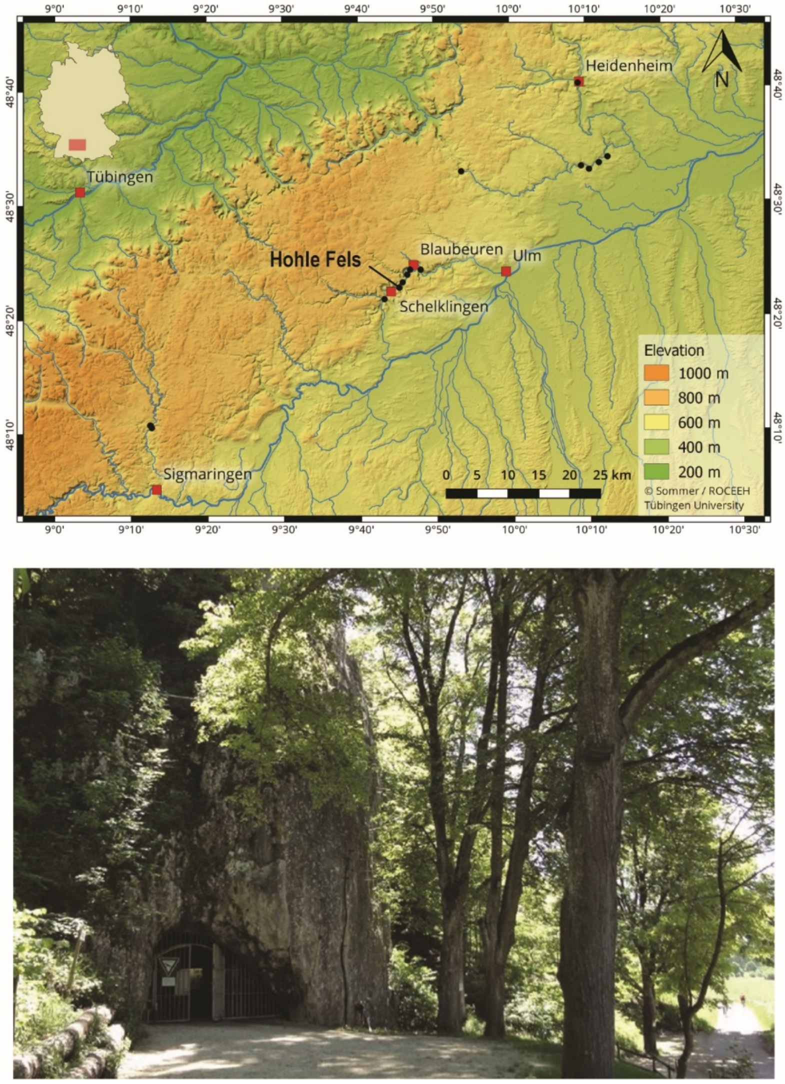

Fig. 3: Map of the Swabian Jura in the southwestern Germany with the location of Hohle Fels. Map courtesy of C. Sommer, University of Tübingen (https:// doi. org/10. 5281/ zenodo. 34603 01). Picture of the entrance of Hohle Fels (D. Marcazzan).

2.2.1 Archaeological assemblages

The many years of excavation have revealed a long sequence of Pleistocene-aged deposits at Hohle Fels (Fig. 4), ranging from the MP to UP. Following the Tübingen stratigraphic approach, the sequence breaks into litho-stratigraphic and archaeo-stratigraphic categories (Goldberg et al. 2003), taking the names of Geologische Horizonte

(GHs) and Archäologische Horizonte (AHs). GHs correspond to Arabic numerals (GH 1, GH 2, GH 3, etc.) (Schmidt 1912; Conard et al. 2012). They are defined on lithological characteristics recognizable during the excavation, including grain-size, colour, fabric, inclusions, and the upper and lower bounding contacts (Goldberg et al. 2003). AHs to Roman numerals (AH I, AH II, AH III, etc.) (Schmidt 1912; Bolus and Conard 2012). AHs are named on the basis of archaeological assemblages (Goldberg et al. 2003). Within this system, the features (Befund) are stratigraphic units on their own. They are lithologically distinct from the surrounding deposits, but they are spatially constrained. Because they are excavated separately, the features have their own analytical unit, although they are assigned to specific AH/GH (e. g. Bef. 16 GH 7aa).

In 2003, Goldberg and colleagues grouped the GHs, with their AHs, into lithostratigraphic using capital roman letters (A, B, C, D, etc.), which broadly correspond with the cultural assemblages. Here I provide a short summary of their descriptions:

- Unit E. The Middle Palaeolithic (>44,000 cal yr BP) covers from GH 15 to GH 8. It usually includes phosphatized calcareous clay from the back of the cave, probably washed downslope (Miller 2015). The primary difference between the Middle Palaeolithic and the overlying layers lies in the density of the finds. The lower GHs appear to have a higher density, while the archaeological material is scarcer approaching the contact with the Aurignacian. The discovery of a leaf point (in German Blattspitze) from gray Jurassic chert (Conard et al. 2021) is of particularly relevance as it is the main raw material used along the Middle Palaeolithic AHs.
- Unit D. The Aurignacian (ca. 44,200-34,280 cal yr. BP) includes GHs from 7 to 3d. In particular, the transition witnesses an abrupt break with the sedimentary trend, changing from highly phosphatized clay (GH 8) to highly calcareous clays (GH 7) (Miller 2015). The sediment from these GHs indicates a relatively warmer period with higher moisture. The biological activity promoted the extreme phosphatization of the matrix (Goldberg et al. 2003; Miller 2015). The Aurignacian assemblage is the richest cultural layer of the sequence. The lithic artefacts are mainly knapped on Jurahornstein (chert) or the local Jurassic chert found on the Swabian Jura (Bataille and Conard 2018). The worked ivory and bones are the distinctive artefact type of the Aurignacian at Hohle Fels (Conard 2003; 2009; Conard et al. 2009). The Venus of Hohle Fels (~38 kya) from ivory, along with the flutes from bones and ivory, are among the most extraordinary objects found in the cave (Conard 2003,

2009). Added to these are Wasservogel (water bird), Kleine Löwenmensch (little Lion-man), and Pferdkopf (horse head) (Conard 2003).

- Unit C. The Gravettian (ca. 34,000–30,500 cal. yr. BP) GHs go from 3c to 3b. The composition is more homogeneous and mainly calcareous (Miller 2015) than the underlying layers. Thin sections from this unit show the typical characteristics of a cold environment, such as rounded aggregates and platy ice-lensing microstructure (Goldberg et al. 2003; Miller 2015). The majority of the raw material used for the typical lithic production of the Gravettian is local, mainly Jurahornfels and Bohnerzhornstein from the Swabian Jura (Conard and Moreau 2004). The organic tools include projectile points made from mammoth ivory, as well as worked bone points, and bone perforated bars and burnishers. The ornamental objects consist of pendants made from teeth, snail shell, and marine shells (Conard 2003; Conard and Moreau 2004), as well as long bones with incisions.
- Unit B and A include the erosional surface and the Magdalenian (GHs from 3ad to 1s) and Holocene (GHs from 1kb to 1ka) layers. Unit B marks a break from the previous units. The sharp contact between Unit B and Unit C highlights a possible erosional event. The Magdalenian (ca. 16,700-13,500 cal yr. BP) preserves phosphatic grains within a calcareous matrix indicating a shift to colder conditions (Miller 2015).The Magdalenian layer uncovered many lithic artefacts, organic tools, and macrofaunal remains useful to reconstruct the activities and the diet of the occupants during this period (Münzel 2001). The lithic artefacts are mainly in the local Jurahornstein and radiolarite (Burkert and Floss 1999). Among the organic tools there are harpoons and projectile points from bones and bone and reindeer. With regard to the macrofauna, horse and reindeer are significant within the layers, along with fox and hare (Münzel and Conard 2004). Along with lithic and bone tools, the Magdalenian layers yielded worked ivory, perforated fox and badger teeth, and perforated snail for personal ornamentation (Rähle 1994), as well as six painted rocks (Velliky et al. 2018).

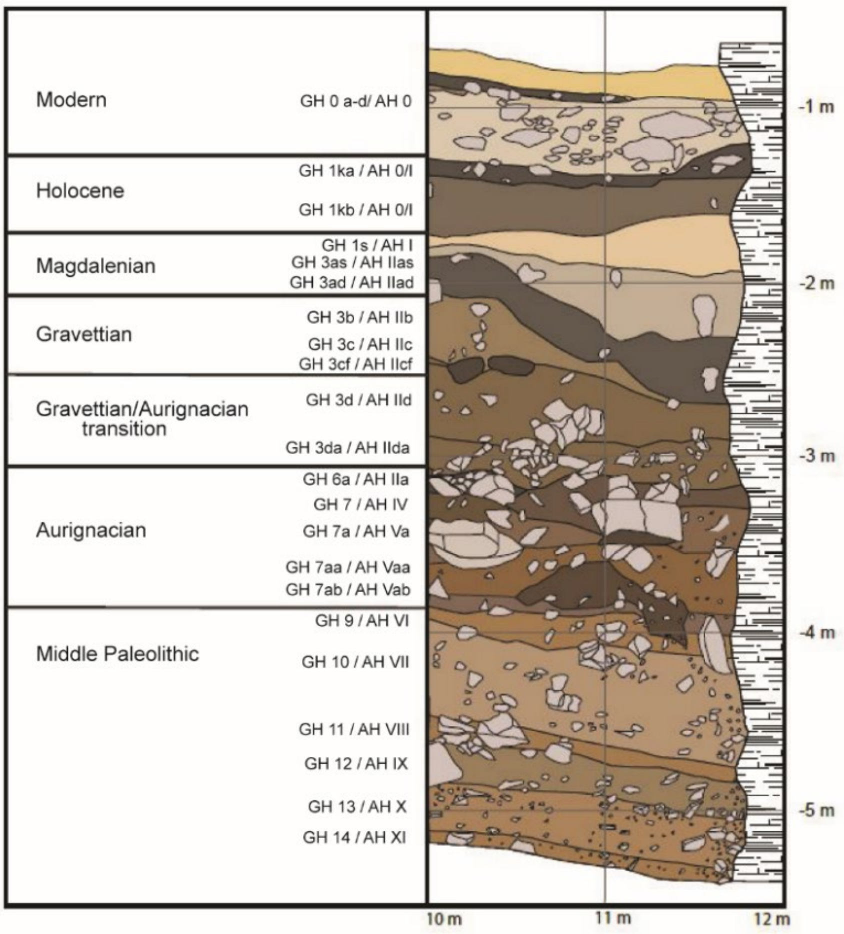

Fig. 4: Stratigraphic profile highlighting the correlation between the geological horizons (GH) and the archaeological horizons (AH) (by A. Janas).

2.2.2 Previous geoarchaeological works

The geoarchaeological studies at Hohle Fels have a long history (Goldberg et al. 2003; Schiegl et al. 2003; Miller 2015; Barbieri et al. 2018, 2021). The studies led by Goldberg and Miller revealed more sedimentary heterogeneity than was observed during the excavation. The main components consist of calcareous and phosphatic clay, éboulis, lithic fragments, bone, charcoal and organic material. Their abundance and consistency establish the differences among the lithostratigraphic units The subdivision of the stratigraphy into units according to their characteristics provided the necessary data to reconstruct a depositional model of the site. Goldberg et al. (2003) and Miller (2015) suggest that blocks of limestone fall from the roof and walls of the cave due to freeze-thaw action. After falling, they were transported downwards as suggested by physical and chemical alteration (Miller 2015). On the contrary, the fine fraction displays a more variable history. Miller (2015) proposed that the clay derives from the karstic system through water percolation. The clay appears often related to aggregates with inclusions of quartz-silt

(Miller 2015) coming from the large chimney at the back of the cave (Goldberg et al. 2003). The sediment, which likely entered through this chimney, began moving down the slope towards the entrance due to cryoturbation. However, this model does not explain why there is an erosional contact between the Gravettian and the Magdalenian (Miller 2015; Barbieri et al 2018). Barbieri et al. (2018; 2021) showed that land formation in the Ach Valley during the Pleistocene and Holocene had stages of soil formation, slope denudation, river valley incision and floodplain aggradation. During the Last Glacial Maximum, this alternation of different phases contributed to the formation, but also to the erosion of the archaeological deposits contained in the caves.

The work done on the features deserves a separate paragraph. An initial analysis of the material from GH 3cf (Waibel 2000) suggested the redeposition of the material from a large hearth inside the cave, although the actual presence or original location of this hearth is unclear (Miller 2015). Weibel assumed that the redeposition of this material occurred due to natural events. In 2003, Schiegl and colleagues performed a micro-contextual analysis of GH 3cf. Its micromorphological analysis revealed a high porosity sediment with no evidence of compaction of burnt and unburnt bone fragments, and little to no post-depositional trampling evidence. Contrary to what was previously argued, they highlighted a strong anthropogenic input of GH 3cf. They attributed it to intentional dumping from several hearths (Schiegl et al. 2003; Miller 2015) and moved the location of the occupation further to the front of the cave.

Miller also analysed four Aurignacian features (1 from GH 8, 1 and 6 from GH 7, and 1 from GH 6a) (Miller 2015). Their properties are very similar to GH 3cf but with a weaker anthropogenic input. They show an adjacent occurrence of combusted materials with varying degrees of burning, no burnt substrate, and high porosity, therefore ascribable to dumping. 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).

Chapter 3 Materials

3.1 Sampling and thin section production

The anthropogenic feature from Fumane Cave and Hohle Fels are the main focus of this dissertation. At Fumane, the samples primarily come from the transition between layers and from possible combustion features to enable a wide coverage and a broad comprehension of the variations within the cave. Thus, the sampling strategy includes oriented monolith blocks, collected systematically. From Fumane I analysed the units A10, A9, A6, A5, A4, A3, A2, and layer D3bAlpha. At Hohle Fels the sampling strategy mainly includes georeferenced monoliths, and, in a few cases, samples taken from the profile. However, the blocks are not taken from every square. From Hohle Fels I analysed 16 features coming from the Magdalenian, Gravettian, Aurignacian, and Middle Palaeolithic layers.

The thin sections preparation took place at the Geoarchaeology Laboratory at the University of Tübingen. After drying in an oven at 40°C, they were impregnated with a mixture of unpromoted polyester resin, styrene, and methyl ethyl ketone peroxide (MEKP) (700/300/5)/L. The hardened blocks were then cut to 6 × 9 × 3 cm slices, mounted on glass, and then ground and polished to a thickness of 30 µm. While the thin section from Fumane (unit from A2 to A9) were produced in the laboratory Massimo Sbrana-Servizi per la Geologia at Piombino (Livorno), without artificial heating and embedded with diluted polyester resin. However, for the unit A10 the thin section were made Geoarchaeology Laboratory at the University of Tübingen and after the blocks were fully hardened, thin sections were then ground by the Terrascope Thin Section Slides laboratory, in Troyes, France.

3.2 Bone treatment, burning, and sample preparation

In order to perform the burning experimentation, we used 4 sets of osteological samples, modern lamb femur (LA), modern roe deer metacarpus (RO), and modern horse rib (HO) and radio-ulna (HOU) (Fig. 5). LA, RO, And HO were macerated in water at a constant temperature (30 °C), while HOU were air-dried. After cutting the bones and removing the periosteum and marrow from HOU, we burnt them at low temperatures from 20°C to 500°C, at 50°C intervals in an oven with oxidizing conditions, Carbolite Gero (30-3000 °C). The heating rate increased by 10 degrees per minute. The temperatures went 10°C above the desired setpoint and then down to the desired temperature in a few seconds. After reaching temperature, we let the bones burn for 45-50 minutes (Thompson et al. 2009) since molecular changes began to occur in bones heated for 15. We then left them to cool for 24 h outside the oven. Because of different fat content, we burnt the HOU separately from the others.

Before the analysis, we cut the samples after the burning using an Isomet precision sectioning saw to avoid damage to the bone structures, and then we dried them in a desiccator for several hours. Half of each bone has then embedded the bone in low viscosity Araldit under vacuum. The polished sections were prepared for microscopic analyses according to the procedures used in organic petrology (Taylor et al. 1998). However, we dry polished the thin sections under very low pressure using a sequence of grinding and polishing steps followed by a final polishing step using aluminium oxide powder. For the other half, after the lipid extraction, we grounded the bones with Mini Mill (pulverisiette23) using 3 stainless steel balls (5mm diameter).

Fig 5: Charred bones. 1) Lamb femur (LA) ; 2) Roe Deer metacarpus (RO); 3) Horse rib (HO); 4) Horse radio-ulna (HOU) (photo by D. Marcazzan).

Chapter 4 Methods

A geoarchaeological approach applies a series of concepts and techniques coming directly from geosciences to answer archaeological questions (Miller 2011; Karkanas and Goldberg, 2018). The application of this approach operates on a different range of scales. The primary goal of the geoarchaeological approach is the understanding of how the geological and environmental processes affected past human activities (Miller 2011) and how humans interfered with the natural processes (Courty 2001). The geoarchaeological technique I mainly used in this dissertation is micromorphology. I supported the micromorphological analysis with other analytical techniques to fully comprehend the anthropogenic features at both sites, and to investigate bone's optical and spectral characteristics.

4.1 Micromorphology

Micromorphology is a technique taken directly from the soil science (Bullock et al. 1985; Courty et al. 1989), which investigates undisturbed and oriented blocks of sediment mounted in thin section (this preparation is described in Chapter 3 of this dissertation). Micromorphological analyses examine the composition and spatial arrangement of the components within a deposit (Stoops 2021). Micromorphological analyses aim to provide a high-resolution interpretation of the depositional and post-depositional processes, and a detailed reconstruction of past human activities within an archaeological deposit (Nicosia and Stoops 2017). Courty (2001) introduced the typical micromorphological analysis concept of (micro-)facies, achieving a systematic classification of multicomponent deposits within sedimentary classes by describing their dominant characteristic (Haaland et al. 2021a). The application of the facies concept helps identify key types of deposits that occur repeatedly throughout the sequence (Miller et al., 2013), facilitating a spatial reconstruction of past human activities (Villagran et al., 2017).

In this work, I used a Zeiss Axio Imager petrographic microscope under plane-polarized (PPL) and cross-polarized (XPL) light. The thin section description follows the works of Courty et al., 1989, (Nicosia and Stoops 2017), and Stoops 2021 in a systematic descriptive template (Marcazzan and Meinekat 2022).

4.2 Organic petrology

Organic petrology is a well-established technique to assess the reflectance of plant tissues to measure the maturation degree of organic matter in peats, brown coals, coals, and sedimentary rocks (Borrego et al. 2006). In soil and paleoenvironmental studies, measurements of reflectance help to characterize charcoal particles (Jones et al. 1991; Guo and Bustin 1998; Bustin and Guo 1999) and the humification process (Jacob 1974). Archaeologists often use organic petrology in the study of combustion features to identify and classify the residues from combustion (Ligouis 2017) and, thus, deduce possible fuel used and burning conditions.

In this dissertation, the measure of the random reflectance in oil (mean % Rr) of the organic particles follows the standard procedure (Taylor et al. 1998). We performed the organic petrographic analysis in reflected white light and in incident ultra-violet light with a Leica DFC550 Digital Camera, using 20x and 50x oil immersion objectives (total magnification respectively: 200x and 500x). We rely on the nomenclature of macerals in brown coal and coal to classify and describe the organic micro-components (macerals) (Taylor et al. 1998; Sýkorová et al. 2005). The measurements of bone reflectance has been taken under oil immersion at a magnification of 500x and a wavelength of 546 nm (monochromatic light), using a measuring diaphragm of 2 µm diameter. On the charred bones, we calibrated the photometer with two standards materials of known reflectance covering the interval of measures: 0.589% (saphir, 546 nm, 23°C), 3.112% (cubic zirkonia, 546 nm, 23°C). We performed at least 100 measurements when the size of the bone sample allowed it. Depending on the type of bone, the measurements are spaced 10 to 40 µm apart along a transect from one edge of the disc to the other. Lastly, we examined the fluorescence to characterize the fluorescence properties of the bones through the temperature range of the heat experiment. The variations of the colours and the intensity of fluorescence will be particularly taken into account and interpreted as the result of the alteration due to burning.

4.3 Fourier transform infrared spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) consists of the identification of the functional mineral groups in a powdered sediment sample, in sediment mounted on a thin section, or in resin-impregnated sediment blocks (Berna and Goldberg 2007; Berna 2017). FTIR is a quantitative analysis useful for determining the mineralogical composition of sediments and archaeological materials (Weiner et al. 2007) to understand their diagenesis and alteration (Berna 2017). This technique has become particularly important in the study of burned materials (Mentzer 2017), through the identification of changes in the crystal structure of clay minerals, carbonates, phosphates, and sulphates caused by heat. In fact, in the spectra from heated bones, peaks changes and appears when increasing the temperature of burning (for a complete overview van Hoesel et al. 2019).

For this study, I employ micro-FTIR and ATR (attenuated total reflection) using FTIR bench (Cary 660, Agilent) attached to a microscope with integrated ATR on polished impregnated blocks and powdered bone samples. Measurements were performed in total reflectance between 4000 and 400 cm-1 wavelengths at 4 cm-1 resolution.

4.3.1 Statistical analysis

The need to quantify and process data obtained from FTIR has led researchers to apply statistical analyses (Thompson et al. 2013) such as principal component analysis (PCA) or linear discriminant analysis (LDA). By recording peaks measurements, we have the possibility to build database and test predictive models. In 2013, Thompson and colleagues tested the validity of five new spectral indices of heat-induced crystallinity change using a statistical classification model to predict the combustion temperature of a validation set. They first applied a principal component analysis (PCA) to understand the strength of relationships within complex data sets (Thompson et al. 2013). Next, they performed a linear discriminant analysis (LDA) that allowed them to construct a statistical classification from a training dataset and classify temperatures without user input.

In our study, we applied a Partial Least-Square (PLS) regression analysis, after performing a PCA to check the data and identify any outliers. PLS build predictive models based on local least-squares fits (Andrade-Garda et al. 2009) when the factors are many and highly collinear (Tobias 1995), like the spectral variables.

4.4 Microscopic X-ray fluorescence spectroscopy

XRF (X-ray Fluorescence Spectroscopy), or micro-XRF when the analysis is limited to a spatial area of the sample, measures the relative intensity and energy of the characteristic radiation emitted by a given substance through exposure to X-rays (Mentzer 2017). Through elemental distribution mapping, micro-XRF can provide information about the elemental and mineralogical composition and identify authigenic minerals (Mentzer 2017). The application of micro-XRF in archaeology is useful for understanding soil formation processes (Voegelin et al. 2007), identifying sources for the material (Mentzer and Quade 2013), understanding chemical effects of the burial environment on bones (Adderley et al. 2007), and characterizing trapped ochre in thin section (Théry-Parisot 2002; Costamagno et al. 2005; Costamagno 2013; Basile et al. 2014; Henry and Théry-Parisot 2014; Vidal-Matutano et al. 2017; Caruso Fermé and Civalero 2019). Moreover, micro-XRF is important for the study of past burning events, including indent calcite distribution and enrichment as a proxy for ash (Courty et al. 1989).

In this study, we used micro-XRF to recognise the colour of oxide staining on bones and distinguish it from the colour due to burning. The thin sections were scanned under full vacuum with both detectors, maximum tube voltage of 50kV and current of 600 microamps with 50 microns spacing, 25 ms dwell per pixel for the thin sections and with 30 micro spacing for the detail map.

4.5 Fabric analysis

Fabric analysis has been employed in many geological deposits and archaeological sites (Théry-Parisot 2002b; Costamagno et al. 2005; Costamagno 2013; Basile et al. 2014; Henry and Théry-Parisot 2014; Vidal-Matutano et al. 2017; Caruso Fermé and Civalero 2019) to improve the knowledge on depositional and post-depositional processes occurring in the formation of the layers. This type of analysis employs the study of the orientation and dip angle of artifacts and geological elements (McPherron 2005). Fabric shape relies upon the relative values of the three eigenvalues (Benn 1994; McPherron 2005, 2018), calculated from the orientation and dip angle data. Archaeologist usually use fabric analysis to determine the disturbance of the archaeological assemblages (Benito-Calvo et al. 2009).

Here, I applied a similar concept to that used by Benito-Calvo et al. (2009) to the Hohle Fels material. The goal was to understand the degree of reworking that the slope had on the features. This concept relies on the separation between geological and archaeological clast (Benito et al. 2009). In my analysis, I took into account only the archaeological material. At Hohle Fels, the orientation data of the archaeological material is recorded during the excavation when an artefact is above a certain size limit, depending on the type of find (1 cm for lithics and 3 cm for bones). Every I find with a significantly long axis is measured with three points using a total station: P1 in the middle point of the topside; P2 in the highest point of the long axis; and P3 in the lowest point of the long axis. I then use these data with a R script (R Core team 2019 statistical software), which I adapted from previous work published by McPherron (2018) and Li et al. (2021).

Chapter 5 Results

Here I present a summary of the results of the conducted research. I subdivided the section into the three main papers that are the backbone of this dissertation. A detailed presentation of the results can be found in **Appendix I, II and III.**

5.1 Middle and Upper Palaeolithic occupations of Fumane Cave (NE, Italy)

Title	**Middle and Upper Palaeolithic occupations of Fumane Cave (Italy): a geoarchaeological investigation of the anthropogenic features**
First Author	Diana Marcazzan
Co-authors	Christopher E. Miller, Bertrand Ligouis, Rossella Duches, Nicholas J. Conard, Marco Peresani
Journal	Journal of Anthropological Science (JASs; ISSN 1827-4765)
Status	Published

The investigation of the anthropogenic features within an archaeological deposit often leads to the identification of a wide range of features (**Section 1.2**), which go beyond the typical hearth. When this analysis takes place at an archaeological site preserving the MP/UP transition, one has the rare opportunity to add diachronic data on the human-fire relationship and occupation of a site.

By analysing the anthropogenic features at Fumane Cave (**Section 2.1**) we saw that only a few of the features represent primary intact hearths. Most of the features show evidence of anthropogenic reworking, such as trampling and dumping. Several features appear multi-layered and preserve an intricate formation history that includes various activities from combustion to site maintenance. Although we did not use a strictly microfacies approach, we set up a classification system based on the microscopic characteristics employing a facies concept.

This system allowed us to connect shared depositional characteristics with the interpretation of human activities. Thus, we created two main groups each containing different features that share the type of activities and degree of resolution: 1) relatively high-resolution, shorter-term events; and 2) lower-resolution, longer term events. The high-resolution group includes a single episode or action and consists of hearths, hearth bases and dumping/reworking features. The lower resolution group is characterized by the development of a surface. It includes laminated features resembling "trample" deposits and a more homogeneous surface, i. e. occupation horizons, remnants of only partially preserved surface and peripherally related to combustion. We created a third category (isolated concentrations of anthropogenic material) in order to include all the features sampled as such but which in thin section did not fall into any of the previous types.

By combining micromorphology and organic petrology on three different Mousterian hearts, we proved the diversity in fire-related behaviours from Neandertals' groups. The organic petrology analysis identified three different fuel sources used in the three features: 1) grass; 2) wood; and 3) a mix of wood and bones. The identification of variable sources for the fuel implies a certain degree of flexibility in the fuel-selection strategies of the Neanderthal occupants of Fumane Cave. Further, humified organic matter is a significant part in all the samples, which suggests a local supply surrounding the site.

5.2 Burning, dumping and site-use at Hohle Fels Cave (SW, Germany)

Title	**Burning, dumping and site-use during the Middle and Upper Palaeolithic at Hohle Fels Cave, SW Germany**
First Author	Diana Marcazzan
Co-authors	Christopher E. Miller, Nicholas J. Conard
Journal	Archaeological and Anthropological Science
Status	Published

It is well known how a hearth can provide new data on the early use of fire and how it is usually seen as the centre around which everyday activities gravitated in the past (**Section 1.3**). This concept also applies when our research questions concern the occupation and maintenance of a site by hunter-gatherer groups. However, archaeological sites do not always preserve direct evidence of fireplaces, and the excavated area does not always correspond to the main location of human occupation.

Our work at Hohle Fels Cave (**Section 2.1**) focused on 16 features. After a first micromorphological analysis, we were able to identify the anthropogenic composition and the recurrent type of features. Among the anthropogenic material, we have burnt bones showing different degrees of combustion, burnt and unburnt ivory, fat char, charcoal, and chert. More specifically, after analysis with XRF it is clear that the colour is mainly due to the burning and only to a superficial extent to manganese staining.

These anthropogenic components are generally found within every combustion feature, except for ivory and charcoals. Only one feature from the Aurignacian (GH 6a Bef 1) presents frequent charcoal, while almost all the others include mainly burnt bone fragments and fat-derived char. Thus, there is not much compositional variation within the features along the sequence. However, the distribution of the components and the microstructure of the features have visible variations. The microscopic variations and patterns allowed us to classify the features into three types: 1) dumped features; 2) scattered residues from combustion features; 3) laminated and trampled features. Although they have different descriptions, the identification of dumped and scattered features appears closely related. Among the 16 features, we identified 15 dumps and one laminated/trampled surface (GH3b Bef 3).

Further, the main processes of sediment accumulation within the cave are directly correlated to a slope (**Section 2.1.2**) having NW orientation and approximately 15° of inclination (Goldberg et al. 2003; Schiegl et al. 2003). Thus, one of the last questions addressed in the paper relates to the degree of the reworking by slope movements. In fact, the presence of this slope has been one of the main issues in understanding the history of the structures and the intentionality of the human action. Micromorphology demonstrates that the vast majority of these features are the result of dumping activity that likely took place on an irregular and tilt surface. The orientation analysis of the lithic artefacts and bones revealed that the archaeological material from outside the features (the Aurignacian GH 7, 7a, 7aa and the Middle Palaeolithic GH 14) are slightly affected by the slope. In contrast, the Aurignacian features (6 in GH 7, 7 in GH 7a, and 16 in GH 7aa) generally appear not reworked from the slope, preserving the original fabric of dumped deposits.

5.3 Microanalysis of experimental heated bones

Title	Experimental heated bones: organic petrology and Fourier Transform Infrared spectroscopy (FTIR) analysis on bones heated at low temperature in oxidizing atmosphere.
Led by	Diana Marcazzan and Christopher E. Miller
People involved	Bertrand Ligouis and Susan M. Mentzer

The analysis of materials found in excavations and thin sections is an essential step in increasing our understanding of human behaviour. In recent decades, the number of studies on archaeological material has grown exponentially. Research has taken place both through experimental work and on archaeological assemblages. The main objectives are the chemical and physical knowledge of the material and, through this, a better understanding of past human behaviour. Within this research, the study of combusted material (view Mentzer 2014 for a review) has a significant place. One of the most studied materials is certainly heated bone. Heated bones constitute an important part of the findings within an archaeological excavation (van Hoesel et al. 2019). Their finding can provide information on the fuel management or maintenance activities at a site.

Our study on heated bones is based on an already extensive bibliography (Lebon et al. 2008, 2010; Thompson et al. 2009, 2011, 2013; Clark and Ligouis 2010; van Hoesel et al. 2019; Lambrecht and Mallol 2020). Through FTIR, statistical models and organic petrology, we analysed a set of four osteological samples (lamb femur - LA, roe deer metacarpus - RO, horse rib – HO, and horse radio-ulna - HOU). Combustion experiments took place under oxidation conditions for temperatures below 500°C (**Section 3.2** for the entire sample preparation).

The predictive models, built on the FTIR spectra using a partial least square (PLS) regression, showed good results at the beginning. The initial r-square on the training sets (HO and HOU) was around 0.98 for the powdered bones and 0.99 for the polished bones (**Figure 3 and 4 Appendix III**). However, by checking the model fit on the validation set (LA and RO), we were not able to reach a correct classification rate able to predict the burning temperature. With both, the full spectra and without the collagen, the Root Mean Square Error was higher than 50.00.

The organic petrology allowed us to create four main ranges of temperatures: 20 °C, 100-150 °C, 200-300 °C, and 350-500 °C. These ranges of temperatures rely on optical characteristics, reflectance properties, fluorescence colour and char appearance (a detailed description of each stage in **Appendix III**). In particular, the fat-derived char appears in the temperature range 350-450 °C and becomes absent if not rare at 500 °C.

Chapter 6 Discussions

6.1 From the field to a microscopic identification of the features

Objective:

- Investigate the nature of the anthropogenic features starting from the data collected during the excavation through the application of concepts and methods typical of geoarchaeology.

I began the study of the combustion features with a review of the excavation reports (**see Appendix I and II**). Both sites are well-documented and, thus, most of the features have detailed descriptions and documentation (**see SI Appendix I and II**). The documentation generally includes a description of the content and characteristics of the sediment, geometric details, images (both digital and manual), and records of the outer limits of the feature recorded with a total station. In addition, each feature is usually sampled with at least one sediment block for micromorphology and loose sediment. This standardized data collection from the field proved to be a fundamental tool for understanding the nature of the features and tracing changes and patterns within the human occupation. Most importantly, it produced a solid basis for linking micro-scale observations to the archaeological context. For example, by comparing the two sites on the basis of descriptions from the excavation, we can state that these are two diverse assemblages of features from this first step. This statement proved valid in the microanalytical study and subsequent contextualisation of the artefact, but not so different in the occupation model.

The analysis of the field documentation led to the micromorphological analysis of these features as well as to the choice of the best strategy for their interpretation. The characteristics of the deposits and the features themselves made it possible to take two slightly different but complementary approaches. In both case studies, after a micromorphological description (**SI of Appendix I and II** for detailed thin section descriptions), I applied a microfacies concept, which allows connecting shared depositional characteristics with an interpretation of human activities (Villagran et al.

2017b). However, I did not apply this concept in its narrowest sense (e.g., Courty 2001; Goldberg et al. 2009; Miller et al. 2013; Karkanas et al. 2015; Haaland et al. 2021a). First applied by Courty in 2001, the microfacies approach is now widely used in many context (Goldberg et al. 2009; Villagran et al. 2011; Miller et al. 2013; Karkanas et al. 2015; Haaland et al. 2021a). The approach consists of identifying classes and subclasses (Karkanas et al. 2015), named microfacies, that occur repeatedly throughout the sequence (Miller et al. 2013). The systematic (Théry-Parisot 2002; Costamagno et al. 2005; Théry-Parisot et al. 2005) identification focus on the presence of different sedimentary components and their structural organization (Miller et al. 2013). This type of spatial analysis incorporate diachronic variation in activities (Goldberg et al. 2009; Miller et al. 2013) or lateral variations in activities (Villagran et al. 2011; Courty 2001). The ultimate goal of a microfacies approach is to build a three-dimensional image of a human occupation at a given time and to describe its evolution (Courty 2001) in relation to other depositional and post depositional events. Within this dissertation, I first noted differences in the microstructure and distribution of the components in the thin section belonging to the anthropogenic features. Second, I classified the individual microstratigraphic units into different types. This strategy provided two different outcomes, described below.

For Fumane's features, I built a classification system on the basis of the micromorphological fabric and textural pattern. A detailed description of each group and type can be found in **Tables 1 and 2 of Appendix I**. As already mentioned in **Section 5.1**, at Fumane the anthropogenic features can be sorted into three main groups that generally correspond to their degree of time resolution. The first group includes shorter-term events, such as features like hearths or dumping/reworking areas. The second group consists of longer-term events, determined by the development of a surface, and includes trampled deposits and occupation horizons. In comparison, the third group comprises all those features that show very little to no anthropogenic content but were categorized as combustion features during the field description stage.

Within this classification, I introduced the distinction between the occupation horizons and the laminated trampled deposits. Overall, the main difference between these two types focuses on the presence or absence of the typical trampling modification and their connection to combustion. The laminated trampled deposit clearly preserves these modifications (Miller et al. 2010; Rentzel 2017), including compaction (massive microstructure), the alternation of different lenses (with anthropogenic and geogenic input), and, perhaps most importantly, the horizontal orientation and parallel distribution of the components. However, their connection with combustion is limited. In comparison, the occupation horizon is an unlaminated, horizontal microunit with localized evidence for in-situ crushing, with no evidence of compaction, no alternation or lamination of layers, and no iso-orientation of the components. Although these kind of horizons are generally the result of human debris, at Fumane the occupation horizon includes mainly burnt material (likely fuel remains) with a combustion signature that has been proven through petrological analysis (**Figure 6 of Appendix I**). Furthermore, the occupation horizon, even though unintentional, was fundamental to the analysis of the occupation rate through the study of anthropogenic features. At the end of the analysis of the Fumane assemblage, I was able to identify a wide range of human activities beyond simple burning. I identified hearths, dumping areas, laminated "trample", and occupation horizons.

The Hohle Fels case, however, looks somewhat different. After the micromorphological analysis, I identified three major types of microstratigraphic units (**see Appendix II** for a detailed description). These are ascribable to dumps, scatters and laminated features. The identification of dumped and scattered features appears closely related, although they have different descriptions. The differentiation between dumps and scatters mainly consists of the quantity of burnt material included in micro-units, and the consequences that this quantity has on the microstructure and fabric. In fact, for the scatter features the anthropogenic material still shows clear signs of combustion, but it is lower if compared to dump features. Hence, it is the geogenic part that determines the patterning and texture of the thin section.

By looking at the position of the samples (**Table in SI of Appendix II**) we can detect scatter and dump units from the same feature to the point that some thin sections contain evidence for both. This coexistence is certainly due to the size of the features (ca. 1 or 2 square meters) but also to the genetic link (Courty 2001; Goldberg et al. 2009; Karkanas et al. 2015) that dump, and scatter features share. In fact, they are two facies genetically connected to the same anthropogenic process but exhibit lateral variation and a repetitive occurrence (**Figure 11 of Appendix II**). Thus, the dumping process at Hohle Fels produces a set of depositional processes (dumping and scatter) acting at the same time. Overall, the analysis on Hohle Fels provided fewer types of features and, thus, fewer related activities. However, it did provide important data on the repetitiveness of these actions. Fifteen features of the 16 analysed included both dump and scatter.

The complimentary use of the field documentation and the micromorphological analysis allowed me to use the microfacies in a broader sense, better adapting the concept to the specific deposits. In fact, the microfacies provided a full understanding of the nature of the features, setting a solid basis for interpretations beyond the mere characteristics of the features.

6.2 Fuel selection strategies

Objectives:

- Apply a complementary, multi-analytical approach to obtain better information on the degree of burning, fuel choices, and degree of natural reworking.
    - Understand the possible fuel selection strategies through the investigation of experimental burnt bones.

Inferring fuel selection behaviour from the analysis of prehistoric combustion features is complicated. Fuel remains are often challenging to interpret in terms of intention or selection processes (**Section 1.3**) and these remains are often found in caves and rock shelters, where complex depositional and post-depositional processes occur further obscuring their interpretation (**Section 1.3**). The investigation of fuel usually relies on the analysis of macro remains (Théry-Parisot 2002b; Costamagno et al. 2005; Théry-Parisot et al. 2005). Here, I investigated fuel remains in thin sections. The potential of a micro-contextual study lies in the fact that, besides the fuel composition, we learn about the context of the fuel and its close relationship to the feature. In particular, we can fully understand whether the material used as fuel is in its primary position (**Appendix I**) or whether it underwent alteration, such as reworking, trampling or staining. Micromorphology cannot fully meet these requirements but is used in conjunction with complementary analyses to reveal the context and interpretation of the fuel remains (**Appendix I and II**).

Through micromorphological analysis, I identified the main components within the combustion features at Hohle Fels and Fumane (an example in **Table 3 of Appendix II**). Both deposits include mainly unburnt and charred bones (in Hohle Fels, the bones also include ivory), fat-derived char, and charcoal in variable quantities. Neither Fumane Cave nor Hohle Fels contains much ash, and the ash present is often affected by post-depositional processes. In Appendix I and II, there is a detailed description of their characteristics and micrographs (**Figure 1 of Appendix I and Figure 3 of Appendix II**).

In both contexts, the bones appear both unburnt and charred. When burnt, they show a wide range of heating temperatures, from low (300-400°C) to high (above 500°C). I established the degree of combustion by describing the microscopically properties and the colour change. Previous research indicates that the variation in bone colour is generally related to the degree of heating (Stiner et al. 1995), however, there is likely some degree of variation between the colour and other optical properties bones from different animal species (Nicholson 1993). Yellow to dark reddish-black colours in PPL suggest that the heating temperatures were between 300 and 400 °C (Stiner et al. 1995; Villagran et al. 2017). A pale brown-grey colour in PPL and a bluish-grey interference colour with an overall milky cast to the birefringence under XPL imply that the temperatures went above 500 °C (Schiegl et al. 2003; Villagran et al. 2017; Mentzer et al. 2017). Related to the bones in both sites, I found fragments of char deriving from the combustion of animal fat or flesh. In thin sections, char appears as an opaque, heterogeneous isotropic particle preserving a high porosity due to the numerous vesicles (Mallol et al. 2017). The presence of char in correlation with bone colouration would suggest temperatures around 300-400°C and only in rare cases over 500 °C (**Section 5.3**). Along with the combusted material of animal origin, I found fragments of charcoal, although this is mainly present in the Fumane deposit. The charcoal appears as opaque in PPL and XPL, and some maintain the typical woody plant structures (Canti 2017).

By integrating organic petrology into the analysis of the Fumane assemblage (**details in Appendix I**), we acquired additional information regarding the charcoal. Within three different hearth bases from Late Mousterian layers, we identified three different fuel types (**Figure 10 of Appendix I**): grass, wood, and a mix of wood and bone. Further, we identified humified organic matter in all studied combustion features from the MP. The plant tissues were not reworked but appeared primarily crushed in-situ, leading to the collapse of their cell walls. This collapse occurred to such an extent that, in one sample, fragments lost their structure completely and appear as aggregates within the groundmass.

The study of Hohle Fels' features also profited from the use of complementary analyses (**details in Appendix II**). As previously discussed, bones are among the main discarded materials in the Hohle Fels' dumping features, particularly charred bone. The charred bones in thin sections show colours ranging from light brown to black, which may be confused with manganese staining (Villagran et al. 2017). The application of elemental distribution maps helped to identify and quantify the degree of Mn staining affecting bone. The results showed that Mn oxides cover the charred fragments only superficially and primarily along the edges (**Figure 8 of Appendix II**). Thus, the material was first burnt and then underwent post-depositional oxide staining.

The results of these analyses lead to several important questions: What does the study of fuel reveal? Why is mainly decayed material found in Fumane? Why did human groups burn mainly bones in Hohle Fels? Interpreting these data helps us answer these questions and provides information on fuel selection strategies and related behavior (Théry-Parisot 2002a, b; Costamagno et al. 2005; Théry-Parisot et al. 2005; Bosch et al. 2012; Henry and Théry-Parisot 2014; Vidal-Matutano et al. 2017; Vidal-Matutano 2017; Caruso Fermé and Civalero 2019; Starkovich et al. 2020; Vanlandeghem et al. 2020). Furthermore, identifying patterns of fuel use by hunter-gatherer societies provides data on the mobility, duration and function of different occupations (Théry-Parisot 2001; Fermé and Théry-Parisot 2020).

Humified organic matter appears in all the combustion features studied from the MP at Fumane Cave (**Appendix I**). It is well established that humified wood burns poorly and only partially (Théry-Parisot 2001) compared to dry wood and, therefore, can appear as the dominant residue, regardless of the original fuel composition. Thus, it would be difficult to quantify the selective use of decayed wood (Théry-Parisot et al. 2010b). Nonetheless, the occurrence of partially humified material in all the analysed hearths suggests that this material represented at least part of the fuel used by Neanderthals. The presence of decomposed wood in-situ within what we have described as hearth bases is highly relevant to the use of fuels by Neanderthals. Other sites revealed the same preferential use and importance of dead wood as fuel, including Abris Pataud, Castanet and Combette (Théry-Parisot 2001; Théry-Parisot and Texier 2006), Abric Romani (Allué et al. 2017), Abric del Pastor and El Salt (Vidal-Matutano et al. 2017). The Neanderthals at Fumane (and likely elsewhere) collected their fuel either at the edge of a river or from the undergrowth of the forested areas near the site. This type of fuel collection strategy may be related to the lifeway of Neanderthals' groups, usually defined by the high mobility on the territory and the seasonal occupation of the site (Théry-Parisot et al. 2005; Théry-Parisot 2006; Vidal-Matutano et al. 2017). Alternatively, it may mirror a specific choice by the Fumane group. Because of its particular characteristics during combustion, dead wood may reduce the combustion time and therefore imply a less intensive fuel harvesting or management strategy (Théry-Parisot 2006). In addition, as Vidal-Matutano and colleagues (2017) wrote, the choice might depend on specific activities, such as cooking, roasting or producing smoke to repel insects, protect from predators and/or have greater visibility from a distance from other human groups.

The high variability of scenarios also characterises the material used as fuel at Hohle Fels (**Appendix II**). Charred bones are dominant over charcoal in the features at Hohle Fels (Schiegl et al. 2003; Miller 2015), especially from the UP layers. Their strict correlation with fat-derived char suggests temperatures around 300-400 °C and only in rare cases over 500 °C (**Appendix III**) usually related to a campfire. The high quantity of bones reflects choices in the type of fuel used for domestic hearths (Théry-Parisot 2002b; Costamagno et al. 2005; Théry-Parisot et al. 2005). The use of bones as the main fuel favours the production of a high flame and also a quick extinguishing of embers (Théry-Parisot 2002b). Furthermore, if used together with decomposed wood, the bones would have amplified the properties of the latter and the combination aids in ease of supply as bones are a common waste product in Paleolithic sites and decomposing wood is more easily obtained than fresh wood, the use of which imposes certain restrictions (Théry-Parisot 2001).

Beyond simple fuel gathering strategies, a search of the literature (Théry-Parisot 2002b) indicates that the use of bone as a fuel source is often correlated with cold environments and scarcity of wood. Previous work at Hohle Fels (Schiegl et al. 2003 and Miller 2015) has also associated this choice with environmental conditions (Riehl et al. 2015). They argued that harsh climatic conditions reduced the availability of wood, forcing occupants to rely on bones. However, I did not observe significant diachronic changes in the proportion of charred bones throughout the Hohle Fels sequence (**Table 3 of Appendix II**). Therefore, I am not able to link the preferential use of bones to a specific time related to changing environmental conditions with these analyses. Additional possible explanations for the high number of charred bones come from the function of the hearths themselves (Théry-Parisot 2002b). For example, it could be related to the function of the fireplace (Théry-Parisot 2002b), where the main intent was convection and radiation, fundamental for purposes such as heating a space/body, protection, cooking/drying and lighting. Lastly, it could be linked to the burning of food waste for site maintenance and subsequent waste removal (Costamagno et al. 2005; Bosch et al. 2012; Starkovich et al. 2020).

In conclusion, the choice of fuel by hunter-gatherer groups is strongly interrelated with the sources available in the landscape. However, as already mentioned in **Section 1.3**, the intentional and behavioural aspects play a key role in the choice. On one hand, intention might include the purpose of a hearth (e. g. heating, lighting, etc.) and the role that the hearth played in the maintenance activities at the site (e. g. waste removal). On the other hand, behaviour remains closely linked to mobility and seasonality, implying certain choices over others. Certainly, we are faced with a complicated system of reasons that is difficult to untangle. However, the use of techniques typical to geoarchaeology and an experimental analysis (**Appendix III**) has brought important data and shed new light on both Fumane Cave (**Appendix I**) and Hohle Fels (**Appendix II**).

6.3 Intensity and duration of the occupation arrangement

Objective:

- Identify any diachronic pattern or change in terms of features, human behaviour, and intensity of occupation by Neanderthal and Sapiens groups within both sites.

Understand the patterns or changes from a stratigraphic sequence is one of the ultimate goals of an archaeologist. Patterns and changes are even more important when speaking of occupation arrangement, group mobility, and intensity of occupation (Wadley 2001; Conard 2004, 2011; Munro 2004; Henshilwood 2005; Stiner 2009). The concept of site occupation intensity (Haaland et al. 2021a) is the result of variable factors such as 1) size of the groups; 2) length of occupations; and 3) frequency of visits (Munro 2004; Conard 2011).

The investigation of these variables often requires the use of interdisciplinary data sets and parallel lines of investigation (Conard 2004). In order to study Palaeolithic settlement systems, previous works have focused on the changes in the density of findings (Porraz et al. 2013; Will et al. 2014; Reynard et al. 2016). However, relying on this data alone may not be sufficient as within the deposit the sedimentation rate may change (Jerardino 2016; Haaland et al. 2021a). Further, archaeology and ethnography tried to understand the behaviour of the human groups by analysing refuse discarded in different populations. Refuse studies proved to be an important source of information on social organization (Needham and Spence 1997), spatial patterning of past activities (Schiffer 1972), population density (Wilson 1994), and degrees of mobility (Murray 1980; Hardy-Smith and Edwards 2004).

Within this framework, a site structure and a site-formation analysis can be used to study the occupation organization and movement patterns of hunter-gatherers (Goldberg et al. 2009; Haaland et al. 2021a). However, it is often a complex task as other processes take place throughout the formation of a site in addition to human activities, especially in caves and rock shelters (Goldberg and Macphail 2006). Thus, the use of a geo-archaeological approach supported by ethnoarchaeological studies of hunter-gatherer groups (Marshall 1976; Yellen 1977; Murray 1980; Binford 1996), is a perfect tool to vertically identify past activities within the deposit (Goldberg et al. 2009) and connect them with the environment and the landscape.

Previous works, mainly on Middle Stone Age sites in South Africa (Goldberg et al. 2009; Wadley et al. 2011; Miller et al. 2013; Karkanas et al. 2015; Haaland et al. 2021a) and on the MP in Israel (Meignen et al. 2007), highlight the importance of a micro-contextual approach to assess the occurrence and variations of activities in hunter-gatherer campsites.

Goldberg and Wadley (2009 and 2011) saw at Sibudu (South Africa) diachronic changes in the type of features and their occurrence. At one point within the stratigraphy, they identified an increase in the intensity of site maintenance activities (Goldberg et al. 2009), such as bedding, secondary waste dumping, and hearth cleaning. This change also seems to coincide with an increase in technological variability (Wadley et al. 2011). Therefore, the authors hypothesized a reduction in residential mobility and an increase in long-term occupations. Comparable examples come from Diepkloof Rock Shelter (South Africa) and Blombos Cave (South Africa). Miller (2013) and Haaland (2021a) highlighted changes in the use of the site over time by characterizing the anthropogenic input. In Diepkloof Rock Shelter, the geoarchaeological investigation (Miller et al. 2013) contributed to the assessment of diachronic variations of the site occupation. For example, a lithostratigraphic unit with increasing evidence of combustion, such as hearths stacked on a stable surface, but no evidence of intensive site maintenance (Miller et al. 2013) hints at relatively short but repetitive visits to the site. In contrast, the growth of maintenance activities in a different lithostratigraphic unit suggests an increase in occupational intensity and a change in the types and arrangement of domestic activities (Miller et al. 2013) of prolonged human visits. This contrast between the absence and presence of maintenance activities, which often overlap, also characterizes the site of Blombos Cave (Haaland et al. 2021a).

However, one does not always see a diachronic change in the type of features. Meignen et al. (2007) argued that the numerous burning events at Kebara Cave (Israel) happened repeatedly, often in the same place or at least in the same area. The intervals of nonhuman occupation were short enough that the next episode of anthropogenic deposition did not completely destroy the previous combustion features leading to a palimpsest. Thus, they suggested intensive and repetitive visits to the cave with a short period of non-deposition. Karkanas and colleagues (2015) at Pinnacle Point 5-6 (South Africa) saw an increase in the frequency of occupation horizons rather than types of features. In particular, the marine isotopic stage (MIS) 5 layers include numerous single, often intact hearths, suggesting a pattern of occupation consisting of shorter visits, presumably by smaller groups. While for the MIS4 layers, the features consist of thick, reworked anthropogenic lenses of burnt material. The authors (Karkanas et al. 2015) ascribed this accumulation to more intensive site use. In fact, they recall a prolonged period of occupation, showing the overlap of human activities. Applying these concepts to the micro-contextual analysis at Fumane Cave and Hohle Fels, I provided the final step in the development of their occupational models.

At Fumane Cave (**Appendix I**), I do not see a diachronic change in the types of human activities. The activities carried out at the site are the same (hearth, dumping, trampling, etc.) for the MP and UP (**Section 5.1**). As previously mentioned, single and often intact hearts usually imply shorter visits (Karkanas et al. 2015). In contrast, thick reworked anthropogenic horizons suggest intensive use of the site. Within my analysis, I used the presence of the occupation horizons (**Figure 11 of Appendix I**) in comparison to single intact hearts and dumping features to infer the intensity of occupation. The occupation horizons are not laterally extensive, and post-depositional events do not appear to have affected their preservation. Therefore, I have attributed these thin, limited patches to intensive site use but given their characteristics to a brief but repeated frequentations. The number of features along with the occupation horizons decreases proceeding towards the MP/UP shift (the Uluzzian), hinting that human groups frequented the site less or more sporadically. This tendency also mirrors the general trends in the density of lithic and faunal materials, correlating the features and other artefacts with changes in site occupation and use. However, within the UP, this tendency reverses. The features appear more 'complex' and often overlapping, and the pattern of use of the site itself seems to be more organised, implying longer-term occupations. This model reveals that these changes do not so much reflect a shift in the pattern of site use. Rather, they are related to changes in mobility strategies, as they coincide with the disappearance of the Neanderthals and the arrival of the Sapiens. The changes in the groups mobility and in occupation intensity also characterizes the Hohle Fels study.

The recurrence (**Appendix II**) of a specific secondary activity in the same place contributed to locating the occupation at the site. There is no noticeable change in the types of features. I found primarily dumping (**Section 5.2**) in Hohle Fels, while the features in Fumane included activities such as burning, dumping, and trampling. Hohle Fels is a complicated site from the depositional-and post-depositional processes (**Section 2.2**) point of view, characterized by a NE-oriented slope that goes from the back of the cave towards the entrance. By using fabric analysis (**see Figures 9 and 10 of Appendix II**), we proved the anthropogenic nature of these features, especially for the UP. The high number of dumped features characterises the excavation area in the apse, ahead of the large hall, which appear to be a designated place for the waste material (as described by Schiffer 1972 and Binford 1978). In addition, the characteristics of these features do not suggest intensive use of the large inner chamber, as there are very few traces of trampling (**Section 1.2**). Thus, the study shows that the location of the living space, at least for the UP, was probably at the entrance (Schiegl et al. 2003), although humans had access to the internal area of the cave. Approaching the interface with the Aurignacian, the MP layers have no features. Only in the lowest layers, currently reached by the excavation, the features begin to be more frequent but also more affected by natural processes. Because of these alterations, the discharge area was probably located further back, hinting at a probable shift in activity for the Neanderthal groups.

Finally, neither the presence of occupation horizons nor the increase in maintenance activities but rather the recurrence of waste disposal in the same place made it possible to build an occupation model. Ethnographic studies (**Section 1.3**) showed a close connection between waste refuse location and the social organization (Needham and Spence 1997), spatial patterning of past activities (Schiffer 1972), population density (Wilson 1994), and degrees of mobility (Murray 1980; Hardy-Smith and Edwards 2004). Murray (1980) writes that formal structuring of waste occurs when groups are semi-sedentary, staying in one place for at least one season. Yellen and Brooks (Yellen 1977; Brooks and Yellen 1987) also suggest that longer periods of occupation lead to a separate location for the production/fuel leftovers. Moreover, Wilson and Kent (Wilson 1994; Kent 1999) record that the freedom to waste refuse indiscriminately decreases as the population density increases. Therefore, a more formalized disposal behaviour would be associated with higher population density (Wilson, 1994).

Accordingly, the attribution of the apse as a waste disposal area (Schiegl et al. 2003; Miller 2015) would suggest that the occupation area was likely closer to the entrance (Schiegl et al. 2003). These observations would suggest that Upper Paleolithic occupation of Hohle Fels had clearly defined division of space. The division may imply longer periods of occupation (Yellen 1977; Brooks and Yellen 1987) or possibly higher population densities (Wilson 1994; Kent 1999). This pattern fits with previous interpretations of changes in occupation intensity across the Middle to Upper Paleolithic transition at Hohle Fels (Conard 2011; Conard et al. 2006, 2012). Below the Aurignacian layers, dumped features, and combustion features in general, are generally absent from the Middle Paleolithic (GH13 to GH9). This absence generally mirrors a low density of finds in Hohle Fels (Conard et al. 2021) and in Swabian Jura (Conard 2011; Conard et al. 2006) 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).

Chapter 7 Conclusion

I began my dissertation by arguing how human interaction with the natural sedimentation makes the archaeological layers unique, and how the deposit should claim its place among the artefacts. In particular, I emphasised that the anthropogenic features, when treated as part of the material culture, can provide a wealth of information by actively becoming the social memory of human actions at the site. Considering the potential that a geoarchaeological analysis can have in the analysis of the features, the ultimate objective of this doctoral project has been to investigate the diachronic pattern or change in terms of features, human behaviour, and intensity of occupation by Neanderthal and Sapiens groups in Fumane Cave and Hohle Fels. I accomplished this in three stages: 1) the traditional micromorphological analysis of the Fumane Cave and the Hohle Fels deposits, 2) experimental work on the combustion of bones in a controlled environment, and 3) the application of a series of complementary analyses to obtain comprehensive information on the history of the features. These analyses demonstrate that a micro-contextual analysis is a key step in understanding the nature of anthropogenic features, and that it is fundamental for inferring past human behaviour, occupational patterns, and group mobility.

It is necessary to highlight the fact that the working done during excavation and sampling must be the basis for a multi-analytical approach and, thus, we began all of the aforementioned analysis with the field descriptions. Often the documentation collected during excavation is one of the few points, if not the only one, that anchors our work to the deposit and provides us with a complete 3D resolution of the processes and their distribution. It is even more true when we talk about anthropogenic features. Their characteristic of being a “laterally and vertically constrained context” (Miller 2011:94) makes it fundamental to pursue a good descriptive routine in the field. This routine should always include detailed descriptions of the content and characteristics of the sediment, drawings, photographs, boundary records taken with a total station, and samples of both block and loose sediment. The rich field documentation of both caves allowed me to apply micromorphology (Courty et al. 1989; Stoops 2021) and the microfacies approach (Courty

2001). The goal was to discover the true nature of their anthropogenic features. With this strategy, I identified several feature types (e. g. hearths, hearth bases, dumps, occupational horizons and laminated/trampled surfaces) attributable to different activities, including combustion and site maintenance/use. By using a wide set of analytical techniques, I could then more deeply grasp their anthropogenic character and their connection to the geogenic side of the deposit and human behaviour. In addition, I combined the analysis of the archaeological material with an experimental analysis of bone material and its reaction to combustion at low temperatures. After all, the material we find in thin sections has its characteristics and reacts according to them. For example, when a bone burn, it undergoes different stages (Ellingham et al. 2015) to which macroscopic and microscopic manifestations are correlated, such as colour change (Stiner et al. 1995; Hanson and Cain 2007; Villagran et al. 2017), fracture patterns and mechanical strength (Thompson et al. 2009), and crystallinity (Ellingham et al. 2015). Thus, the material analysis is an intrinsic part of research into human activities. Therefore, given the high presence of burnt bones at Hohle Fels, experimentation on bones burnt at low temperatures provided a framework and basis for a more in-depth study of bone assemblage. The solely FTIR analysis cannot be the answer and is the only technique used to identify burnt bones. It is a useful tool to trace changes, and it works especially in a frame of low-medium-high temperatures. However, at the low-medium temperature, it must be used carefully and with the support of other techniques such as organic petrology.

Yet, this doctoral dissertation has not only focused on identifying and classifying the anthropogenic features of the sites. It also addresses how we infer human behaviour, the occupation of sites and the mobility of the groups that inhabited them. Both cases analysed fit into the limited but growing group of studies focusing on the micro-contextual approach and sediment analysis (Meignen et al. 2007; Goldberg et al. 2009; Wadley et al. 2011; Miller et al. 2013; Haaland et al. 2021a see references for a complete overview) to understand the human past (Mallol and Mentzer 2017). First, Fumane Cave and Hohle Fels showed how the micro-contextual analysis of the features is a privileged tool for associating humans with their fuel strategies, as they do not just show what the fuel was made of but also show it in context (Mallol and Mentzer 2017). In Hohle Fels, the features consist mainly of charred bones, denoting a low variation of fuel selection. Thus, the material burnt was likely related more to the purpose of the burning than to environmental reasons or group mobility. On the contrary, in Fumane Cave, the fuel documented a high variation of selection - grass, wood, and a bone-wood mixture - in the MP, together with the recurrent presence of humified plant material. Here, the fuel composition suggests a flexible strategy and is likely combined with other strategies as part of a highly mobile settlement system. Second, both caves and their features have benefited from a micro-contextual and multi-analytical approach.

The Fumane and Hohle Fels cave study has shown how the accumulation rates of hearth features, can provide us with information on occupation intensity. With due caution (Domínguez-Rodrigo and Cobo-Sánchez 2017; Jerardino 2016; Hiscock 1981) and in the context of interdisciplinary research (Conard 2004), through this type of study we can infer, on a larger scale, the increase or decrease in population densities. This analysis showed how it is possible to reconstruct occupational models and produce hypotheses on the mobility of hunter-gatherer groups through a micro-stratigraphic study. At Fumane, we see the repeated short occupations, which characterise the MP, becoming less and less frequent as the transition layers approach, and this also occurs at Hohle Fels on a less prominent scale. In fact, the lower MP layers at Hohle Fels see more intense visits than the layers near the interface with the Aurignacian. A close relationship between the two caves comes also in the UP layers. Both sites show evidence of long-term occupations. What differentiates the two sites, however, is the spatial organisation of the features. While at Fumane there is no distinction of areas, and no internal arrangement of the site, at Hohle Fels there seems to be a strong separation between the main occupation area and the place used for dumping waste material.

A final goal is that this dissertation will further encourage archaeologists to consider anthropogenic features as part of the cultural material. The finding of an anthropogenic feature, especially ones related to combustion, is comparable to many other artefacts and must be treated as such. My results clearly show the amount of information that anthropogenic features can provide, particularly regarding past human activities. These activities took place in a dynamic environment consisting of natural processes and human behaviour, both leaving their mark on the deposit. This thesis has demonstrated again that the combination of a micro-contextual approach and sediment analysis are, therefore, essential in archaeology.

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Appendix I

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Middle and Upper Paleolithic occupations of Fumane Cave (Italy): a geoarchaeological investigation of the anthropogenic features

Diana Marcazzan[1], Christopher E. Miller[1,2], Bertrand Ligouis[1], Rossella Duches[3], Nicholas J. Conard[1,4] & Marco Peresani[5,6]

1) *Institute for Archaeological Sciences and Senckenberg Centre for Human Evolution and Palaeoenvironment, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany*
e-mail: diana.marcazzan@uni-tuebingen.de

2) *SFF Centre for Early Sapiens Behaviour (SapienCE), University of Bergen, Post Box 7805, 5020 Bergen, Norway*

3) *MUSE - Museo delle Scienze, Corso del Lavoro e della Scienza 3,38123 Trento, Italy*

4) *Department of Early Prehistory and Quaternary Ecology, University of Tübingen, Schloß Hohentübingen, Burgsteige 11, 72070 Tübingen, Germany*

5) *Department of Humanities, Section of Prehistoric and Anthropological Sciences, University of Ferrara, Corso Ercole I d'Este, 32, 44100 Ferrara, Italy*
e-mail: marco.peresani@unife.it

6) *Institute of Environmental Geology and Geoengineering, National Council of Research, Piazza della Scienza 1, 20126 Milano, Italy*

Summary - *Here we present the results of a microcontextual analysis of purported combustion features recovered from Middle and Upper Paleolithic occupations at the cave site of Fumane, Italy. Our analyses, which integrate micromorphology with organic petrology, show that only a few of the features represent primary, intact hearths; some of them show evidence for various phases of anthropogenic reworking, either through trampling or sweeping and dumping. Several of the features are multi-layered and reflect a complex formation history of various activities related to combustion and site maintenance. Many appear to be the remnants of occupation horizons only partially preserved and peripherally related to combustion. Within several of the intact hearths from the Mousterian, we were able to identify variable fuel sources in different features, implying a degree of flexibility in the fuel-selection strategies of the Neanderthal occupants of Fumane. In this study we design a classification system of the anthropogenic features and also conduct a spatial analysis, through which we can infer diachronic patterns in the frequency and intensity of site occupation and the spatial distribution of activities. We note a decrease in frequency of combustion features throughout the Mousterian which continues into the Uluzzian. The features associated with the Protoaurignacian occupation, in contrast with those from the Mousterian, are multi-layered and well-defined. We argue that these trends, which correspond with other trends in artefact frequency, imply changes in the settlement dynamics of the site during the transition from the last Neanderthal occupation of the cave to the arrival of modern humans.*

Keywords - *Paleolithic, Cave, Combustion features, Living space, Micromorphology, Organic petrology.*

Introduction

The role that fire played in human evolution is crucial and well established, and its investigation has been the focus of archaeological and anthropological research for decades (Gowlett 2006; Karkanas et al. 2007; Roebroeks and Villa 2011; Sandgathe et al. 2011a,b; Fernández Peris et al. 2012; Shahack-Gross et al. 2014; Stahlschmidt et al. 2015; Sorensen 2017). The international debate pays close attention to the colonization of the areas outside of Africa (Roebroeks and Villa 2011) since the timing of human control of fire in Europe is controversial. Evidence suggests that, within the European context, the habitual control and use of fire became the norm only from the second half of the Middle Pleistocene, around 300-400 ka (Roebroeks and Villa 2011). One of the main points of the debate, besides the ultimate domestication of fire (Roebroeks and Villa 2011; Sandgathe et al. 2011a), concentrates on the kind of relationship Sapiens and Neanderthals had with fire (Dibble et al. 2017, 2018b; Sandgathe et al. 2011a,b; Sorensen 2017). The site of Fumane, which contains numerous combustion features spanning both the Middle and Upper Paleolithic, allows us to investigate the nature of fire use by both Homo sapiens and Neanderthals.

The study of traces of fire preserved within archaeological deposits (i. e. combustion features) (Mallol et al. 2017) is one of the most direct ways of recovering information on past fire-related behaviours (Leierer et al. 2020). The presence of combustion features at an archaeological site implies not only a series of abilities (Bellomo 1994; Clark and Harris 1985) and actions, such as acquiring or producing fire, but they can also provide important information on subsistence strategies (Brown et al. 2009; Goudsblom 1986; Mallol et al. 2007), technological innovation (Aranguren et al. 2018; Schmidt et al. 2019), social organization (Kuhn and Steiner 2019), and adaptation to different environmental conditions (Gowlett 2006; Preece et al. 2006; Rolland 2004; Wrangham et al. 1999), all of which play a crucial role in our understanding of human behavioural evolution. Thus, a detailed investigation of combustion features within a site can not only provide new data on human interaction with fire but can also provide a more complete view of the activities, their spatial distribution, and the range of site maintenance strategies adopted by past human groups at a site (Goldberg et al. 2009; Haaland et al. 2020; Karkanas et al. 2015; Miller et al. 2013; Wadley et al. 2011). In particular, an in-situ combustion structure can provide direct evidence of fire use (Stahlschmidt et al. 2015) but can also be a direct link to the location of an occupation surface (Mallol et al. 2013) and provide information about continuity and change in human behaviour over time, both inside and outside the site (Mentzer 2014). Therefore, combustion features, and anthropogenic features in general, should be treated as part of the material culture of an archaeological site, on par with other classes of artifacts (Berna and Goldberg 2008; Miller 2011).

The term “combustion feature” refers to any feature at an archaeological site that contains the physical evidence of fire (charcoal, ash, heated sediments, etc.) (Mallol et al. 2017). Therefore, combustion features encompass a wide range of features, such as hearths, destruction layers, kilns, and ash dumps. Mallol et al. (2017) proposed a classification scheme for combustion features that focuses on whether the burning event was contained or uncontained; however, they also point out that it is important to distinguish between combustion features that are intact and those that are reworked. With intact combustion features, we imply features containing physical by-products of fire (Mallol et al. 2017) found in their original position of burning. In the best-case scenario, these features display the typical tripartite sequence of horizontal layers: a rubified substrate overlain by charred organic matter, and an ash micro-unit on the top (Meignen et al. 2001, 2007). This microstratigraphic sequence often displays sharp and abrupt contacts. The structure of these sequences depends on several factors (Aldeias et al. 2016) such as fuel choice, the nature of the substrate, duration and setting of the burning event and post-depositional processes (Mentzer 2014). It is not always easy to trace the remains of a combustion feature, considering that a fireplace may represent a relatively short-term event (Aldeias et al. 2012; Karkanas and Goldberg 2019). Additionally, these features might have a variable nature within an archaeological site, since their preservation depends on both depositional and post-depositional processes that impacted the deposit. Geogenic and biogenic processes can affect the preservation of the intact combustion feature, making their identification more complicated.

Although natural depositional and post-depositional processes can impact the composition and character of archaeological combustion features, human actions accompanying or following the initial burning of fuel can also significantly impact the preservation and appearance of a combustion feature. Intentional or unintentional human reworking can occur during the use of the hearth (raking out, dumping, and sweeping) or after abandonment of the feature (i. e. trampling). The burning of fuel within a fireplace, and the subsequent trampling, sweeping or dumping of the combustion remains, can leave traces in archaeological deposits that are readily recognizable through micromorphological analysis (Mallol 2013; Miller et al. 2010).

Using the techniques of micromorphology and organic petrology, the goal of this study is to provide a detailed investigation of the anthropogenic features from Fumane Cave. This work follows on two previous micromorphological studies conducted at Fumane (Cremaschi et al. 2005; Peresani et al. 2011a) and complements a detailed investigation of the geogenic formation processes at the site (Kehl et al. in prep). The initial study by M. Cremaschi investigated the entire stratigraphic sequence and provided preliminary data on the depositional and post-depositional processes acting within the cave (Bartolomei et al. 1992; Cremaschi et al. 2005). The work of Peresani et al. (2011a) focused on layer A6 (Mousterian), providing insight into the geogenic and anthropogenic processes within this single layer. Here, we present our analysis of the anthropogenic features including (1) a micromorphological analysis of the combustion features excavated so far and (2) an organic petrological analysis of samples of combustion features from the Late Middle Palaeolithic contexts. With our results, we developed a classification system of anthropogenic features at the site in order to fill the gap between excavation, sampling strategies and laboratory analysis, but also to examine how the study of anthropogenic features from Fumane adds to our understanding of the occupation and use of the site during the transition from the Middle to the Upper Paleolithic.

Site setting

Fumane Cave, situated at 350 masl, lies in the western part of Veneto Pre-Alps in north-eastern Italy. The site is located at the foot of a fan-shaped plateau, which reaches 1500-1600 masl, that turns gently towards the alluvial plain of the Adige River. Because of its location, the cave is considered a strategic point on the boundary between the alpine meadow and coniferous forest, making it a crucial campsite for access to different types of environments and raw materials (Romandini et al. 2014).

The cave is set within a fossil karst complex formed during the Neogene. It opens at the base of a carbonatic sandstone cliff (Ooliti di San Vigilio Formation, Upper Lias) composed of alternating massive banks of oolithic sands with typical cross lamination and micritic banks separated from the former by a discontinuity (Masetti 2005; Abu Zeid et al. 2019). In the area where the cave opens, the Ooliti di San Vigilio formation is extensively dolomitized. The site, belonging to a complex karstic system, is composed of a large, entrance area and three cavities, and preserves a remarkable stratigraphic sequence of Pleistocene-aged deposits. The first investigations of the site took place in 1964 and 1982 (Broglio and Cremaschi 1989; Cremaschi et al. 1986), but it was only in 1988 that intensive excavation by the University of Ferrara began, focusing on the main chamber.

Stratigraphy

The Pleistocene sequence is 12 m deep and subdivided into four macro-units (S, BR, A and D) defined according to their lithological composition, pedological features, and cultural remains (Cremaschi et al. 2005; Abu Zeid et al. 2019). Our interest focuses on macro-unit A because it spans across the transition from the Middle to Upper Paleolithic and preserves the primary evidence for intense and repeated occupation inside Fumane (Broglio et al. 2003; Peresani et al. 2011a, 2012). Macro-Unit A has been the subject of extensive recent excavations includes a series of units mostly consisting in horizontal, alternating layers (A13 to A1) of aeolian dust (loess), dolomitic sand, and roofspall that tilt weakly towards the outside of the cavity (Cremaschi et al. 2005). There is clear evidence for frost action in these layers too. Finally, macro-unit D (Debris) formed through the collapse of the vault and consists of large boulders in a fine sandy matrix. This unit accumulated before sealing the entrance of the cavity, recorded human and animal use of the cavity (Bartolomei et al. 1992).

Materials and Methods

The present study focuses on a microcontextual investigation of the anthropogenic features found in units A10, A9, A6, A5, A4, A3, A1, A2, and layer D3bAlpha (from A9 we analysed the thin section already prepared since on the field note the features from this layer have common characteristics) (Tab. 1 Supplementary Material). We employ micromorphology as the main technique but augment the results with data obtained through organic petrographic analysis of thin sections and polished blocks.

Micromorphology

Micromorphology is the study of undisturbed and oriented blocks and thin sections of sediments under transmitted light in order to identify the composition of a deposit's constituents and their spatial relationship to one another (Courty et al. 1989; Goldberg and Macphail 2006; Stoops 2021). It is an essential tool in geoarchaeological research that can provide a high-resolution view of the depositional and post-depositional processes that affect the deposits of an archaeological site (Stoops 2021). Moreover, the microscopic analysis of anthropogenic components of a deposit allows for a detailed reconstruction of past human activities in and around an archaeological site.

In Fumane Cave, the oriented blocks are usually collected systematically from whole squares as well as microunits during the excavation, especially where changes in the sediment characteristics were noted and from possible combustion features. The Massimo Sbrana-Servizi per la Geologia laboratory at Piombino (LI) Italy produced the thin sections from A2 to A9 units without artificial heating and embedded with diluted polyester resin. The Geoarchaeology Laboratory at the University of Tübingen processed the samples collected from unit A10. After drying in an oven at 40°C, they were impregnated with a mixture of unpromoted polyester resin, styrene, and methyl ethyl ketone peroxide (MEKP) (700/300/5)/L. After the blocks were fully hardened, thin sections were then produced by the Terrascope Thin Section Slides laboratory, in Troyes, France. We conducted 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) in a systematic descriptive template (Marcazzan and Meinekat 2022).

Organic petrology

We carried out the organic petrographic analysis on two polished sediment blocks (MM25 from A9_SXX and RF-19-31 from A10IV_SVIII) and a specially polished thin section (sample MM31 from A6_SII), finished with a multistep, dry fine polishing (without lubricants). The petrographic analysis under oil immersion (Ligouis 2017) relies on a Leica DMRX/MPV-SP microscope photometer in reflected white-light (RLo) and incident ultra-violet light (UVLo), and in plane polarized (RPPLo) and cross polarized light (RXPLo). Meanwhile, the identification of the organic components relies on magnification ranging from 200x to 500x. The description and classification of the organic micro-components (macerals) follows the nomenclature of macerals in brown coal and coal (Sýkorová et al. 2005; Taylor et al. 1998;).

The determination of reflectance of plant tissues is an established method used to measure

Tab. 1 - Characteristics of the hearths, hearth-bases, and dumping/reworking areas.

FEATURE TYPE	SUBTYPE	MICROMORPHOLOGY AND ORGANIC PETROLOGY	NOTES
Hearth	Typical micro-stratigraphy of an intact hearth (Mentzer 2014)	Distinctive micro-units (top to bottom): Ash micro-unit (grey) Frequent ash with visible calcium carbonate pseudomorphs of prismatic crystals Organic micro-unit (very dark brown-black) rich in burnt mixed material Well-defined layer usually characterized by undifferentiated b-fabric Abrupt contacts Geogenic micro-unit (light brown-yellow) Not observed evidence of heating of the primary substrate Pedofeatures mostly relates to frost action: Thick microlaminated cappings observed in all the microunits Within micro-unit (1), cappings includes ash Organic petrology: Woody or herbaceous tissues, rare fat-derived char, all of which appears crushed in situ (without reworking), leading to the collapse of their structure	Micro-unit 1: It can show cementation and bedding Ash is often exposed to weathering Micro-unit 2: Contains Burnt and calcined bones, charcoal, burnt limestone, fat-derived char fragments, and other organic matter Chert debitage, often exhibiting thermal alteration Examples: Unit A10 feature SI and A6 features SXV and SXXV Two hearths show microstratigraphic evidence for two consecutive burning events: S17 (Protoaurignacian) A10IV_SVIII (Mousterian) (Fig. 2)
	Changes in colour of aggregates and groundmass	Distinctive micro-units (top to bottom): very dark brown or black Preserves more burnt elements (burnt bones and charcoals) Red or dark reddish-brown Light reddish-brown or yellow Gradual contacts between the microunits	The colour change strictly correlates with the clay aggregates (Fig. 3) The multiple origins of the aggregates (allochthonous and autochthonous) do not interfere with colour change Examples: Unit A6, features SV and SVII (Fig. 5), and unit A5 feature SI
Hearth-base		Distinctive micro-unit: One single micro-unit, at the top, consisting of Organic matter and charcoal fragments Undifferentiated b-fabric Abrupt interface with the underlying micro-units Organic petrology shows: Charcoals appear burned to partially humified and characterized by droplets of humic gels attached to the cell walls	No evidence of the typical hearth sequence No ash Examples: Unit A5 features SIII and unitA9, feature SXXI (Fig. 4)
Dumping/reworking area		Distinctive micro-unit: Black to dark brown colour Rich in organic matter and anthropogenic material, both burnt and unburnt Poorly sorted Highly interconnected voids, open-spongy microstructure Components: Different sizes from coarse sand to fine gravel Random distribution and orientation No evidence of compaction or in situ snapping or cracking of bones In a few cases rolling pedofeatures, such as coatings around the coarse fraction	Identified in the field as areas with concentration of dark sediment, no sublayers and random orientation and inclination of the components Not common within the Fumane deposits, although it might be biased due to sampling strategy and/or that dumping occurred in uninvestigated areas of the site Examples: Unit A6 features SI, and unit A10 feature SV-SIX.

the maturation degree of organic matter in peats, brown coals, coals, and sedimentary rocks (Borrego et al. 2006). In soil and paleoenvironmental studies, measurements of reflectance help to characterize the humification process (Jacob 1974, 1980; Schwaar et al. 1990) and to characterize charcoal particles (Bustin and Guo 1999; Guo and Bustin 1998; Jones et al. 1991). We measured the random reflectance in oil (mean % Rr) of the organic particles according to standard procedure (Taylor et al. 1998).

The photomicrographs obtained during the organic petrographic analysis and presented here are in reflected white light and in incident ultra-violet light, taken with a Leica DFC550 Digital Camera, using 20x and 50x oil immersion objectives (total magnification respectively: 200x and 500x).

Results

Field observation

Based on the reports of the excavators (Supplementary Material B), the most common shapes of the combustion features at Fumane are circular or subcircular, although features with an elongated or elliptic shape were also reported. The excavators noticed some with irregular morphology, with undulating and wavy contacts, which they ascribed as indicating post-depositional alteration. The diameter of the features generally ranges from 20 to 50 cm and in rare cases up to 1 m, while the depth generally ranges between 4 to 10 cm. Many features preserve several sublayers that were also discernible during the excavation. On average, there are between 2 or 3 sublayers, while few features, the more complex ones, have 5-6 sublayers. Colour (usually greyish, blackish, dark brownish or reddish) and the material content were the primary means of differentiating these sublayers during the excavation.

The excavators categorized the anthropogenic features encountered during excavation into a number of different types, including what they called buca di palo (postholes), a bacino (basin), lente (lens) or planare (flat). The features that they called postholes usually displayed clear limits with the surrounding sediment. They were filled with vertically oriented anthropogenic material and did not contain any internal sublayers. In contrast, the basin-like features displayed a deeper profile (usually up to 6 cm) and had an internal structure, including several sublayers. Within these observations, the flat type stands for a layered feature with a more regular shape than a lens type. In fact, lenses are those features usually more discrete, often described in a range of 1-2 cm of depth with very few if any sublayer and with an irregular shape. However, the final field interpretation (Tab. 2) usually does not derive from a standardized description.

Postholes and basin-like features are the most common within the Protoaurignacian, with postholes only in unit A2 (Bartolomei et al. 1992; Broglio et al. 2003). From A2 (Supplementary Information), the features appear well-stratified, and the majority in relation to large limestone boulders. Basins and flat features are present also in the Uluzzian (Peresani et al. 2016). On the other hand, lenses and flat features (Supplementary Information) are typical for the Late Mousterian (A10, A9, A6, A5, and A4), where the excavators identified them mainly by a slight change in the sediment colour and from the presence of few burnt materials (charcoal and burnt bones).

Micromorphological results

The analysis of the thin sections provides not only new, detailed information on the evidence of human activities at the site, but also helps elucidate some of the natural depositional and post-depositional processes that were active in Fumane Cave. We described all 86 thin sections from combustion features collected at Fumane (Table Supplementary Material) noting not just the components but also microstratigraphic units, microstructure, pedofeatures, etc. Detailed descriptions of the thin sections are included in the supplemental information. Below we provide information on the anthropogenic components, whereas the geogenic and biogenic components are into the supplementary

***Tab. 2** - Characteristics of occupation horizons, laminated anthropogenic features, and isolated concentrations of anthropogenic material.*

Feature type	Micromorphological characteristics	Notes
Occupation horizon	Distinctive micro-unit: Very dark brown to black groundmass Heterogeneous mix of burnt and unburnt anthropogenic components (charcoals, bones, and derived-fat char), biogenic components, within prevailing geogenic matrix Complex microstructure (channel-vughy) Lenticular microstructure when associated with thick cappings and link cappings Unlaminated, horizontal microunit with localized evidence for in situ crushing Rare evidence of trampling Pedofeatures mostly relates to bioturbation: Common passage features such as burrow Organic petrology: Charcoals derives from woody tissues (rarely from grass). Burning ranges around 250-400 °C Charcoals are either well-preserved, crushed in situ and compressed, without a planar orientation of the components suggesting that they were affected by reworking	Occur mainly in the atrial zone of the cave Excavators described these features as combustion structures, noting their appearance as darker patches with higher concentration of burnt material, charcoal, and organic matter Due to anthropogenic input and its horizontal development, this black microlayer might reflect the activity of the cave's occupants Examples: Unit A9, features SXXI (Fig. 4) and SIX, or A4, feature SI, or A2, feature S16
Laminated anthropogenic feature	Distinctive micro-units: Upwards of three or more micro-units Abrupt interfaces between them Groundmass exhibits a close porphyric c/f-related distribution Typical modifications attributed to the trampling process (Banerjea et al., 2015, Miller, 2017; Rentzel et al., 2017): Compaction Causing a massive microstructure, made by the alternation of different lenses of sediment compressed during or after the deposition Horizontal orientation and parallel distribution of components, such as bones, charcoals, and mica	Indicative of the intensity of the use of space at a site Development of laminated bedding structures, arranged in an alternating sequence of several layers, described as trampled occupation deposit (Banerjea et al., 2015) and identified as the accumulation of various mineral and organic components during the occupation (Rentzel et al., 2017) Examples: Unit A9 feature SXI (Fig. 3), or A2 feature S20
Isolated concentration of anthropogenic material	Distinctive micro-unit: Distinction between feature and non-feature not always identifiable Components include material with geogenic, and biogenic (very few-rare anthropogenic) origins mixed Not a proper arrangement Microstructure usually complex microstructure (vughy-channel-lenticular) C/f-related distribution often porphyric or chitonic when the calcite sand is dominant	In the field, these features generally appeared as dark stains or shadows with more archaeological material compared to the surrounding sediment They have a lower anthropogenic input Examples: Unit A9, features SIII and SV, or A6, features SVI and SXVI

material. The results of the micromorphological analysis are summarized in figures 2, 3, 4, and 5 and include data on the microstratigraphy of the various features.

Anthropogenic components

The anthropogenic features are defined in the field as such based on the high concentration of anthropogenic materials concentrated within a discrete area. The thin section analysis of these features confirms that anthropogenic components make up a significant part of the features and that many of these anthropogenic components have been influenced by heating.

We noted the presence of a few chert fragments (Fig. 1D) ranging from fine to coarse sand size (few also at cm size) with angular and sharp edges. These are ascribed to the debitage of the intense and repeated knapping that took place within Fumane Cave (Delpiano et al. 2018; Falcucci and Peresani 2018; Peresani 2012; Peresani et al. 2017). Very few preserve the cortex surface, indicating that the raw material was likely introduced to the site and then worked. In addition to evidence for weathering that is concentrated mainly on the cortex surface, some of these chert fragments show the development of an internal fine pattern of cracks, which, as seen in experimental studies, may be related to heat damage that begins to appear at 400°C (Angelucci 2017; Domański et al. 2009).

One of the main proxies for activities related to fire is the large number of burnt bone fragments. Although their abundance and size differ between features (from very fine sand up to fine gravel), they are primarily subangular or subrounded with smooth surfaces. Burnt bone fragments are usually present in micro-units rich in organic material, charcoal, or other burning by-products. They exhibit variations in their colour and optical properties depending on the degree of burning (Mallol et al. 2017). The colour range indicates that they were likely heated to a temperature between 300 °C and 400 °C (Fig. 1A), with some cases above this range. Indeed, there are rare, very fine to fine sand-sized fragments of calcined bones (Fig. 1B), with lower order interference colours from bluish grey to grey with a milky cast, typical of bones burnt between 800 °C and 1000 °C (Villagrain et al. 2017a). There are also rare fragments of char, likely derived from animal fat (Fig. 1F). This amorphous organic residue, produced from the burning of flesh and fat, appears in a few features as an opaque-black fragment with high porosity due to the numerous vesicles of varying size and distribution and with small fissures or cracks (Goldberg et al. 2009; Ligouis 2017; Mallol et al. 2017).

Charcoal (Fig. 1C) is mostly present as very fine-to-medium sand-sized fragments, with some falling within the fine gravel size. The charcoal appears as opaque fragments in plane and crossed polarized light and some maintain the typical woody plant structures. Some is found in discrete microunits composed almost exclusively of charcoal, whereas others are found distributed randomly in the matrix.

Another important anthropogenic component that we noted in the thin sections from Fumane and that is linked with fire activity is ash (Fig. 1B) which is present in the form of calcite (CaCO3) pseudomorphs derived from the decomposition through heating of calcium oxalate crystals, a biogenic part of many woody species (Canti 2003; Canti and Brochier 2017 2017; Shahack-Gross and Ayalon 2013). Within the deposits at Fumane, ash residues are mainly concentrated in units A6 and A10, with a few examples found in A2 and A9. Ash is present with its typical rhomboidal shape; however, it often appears altered by both chemical and mechanical post-depositional processes. Chemical alteration is recognizable through partial dissolution and recrystallization of the rhombs. On the other hand, ash rhombs that have been mechanically altered retain their typical shape and birefringence but are found as components within rounded aggregates.

Another possible proxy for burning in Fumane comes from the heat alteration of clay aggregates (supplementary information), both those derived from soils and those from endokarstic sources. In some of the anthropogenic features, the clay aggregates show a clear change in colour throughout the thin section, from a light orange at the bottom to a dark red at the top that may be indicative of increasing of the heat. There is also evidence from the limestone fragments for heat alteration of biogenic elements as a few limestone fragments appear burnt, with cracks, desegregation, and alteration of the calcite minerals.

The last anthropogenic constituent consists of material containing mineral phases of Fe oxides that Cavallo et al. (2016) identified

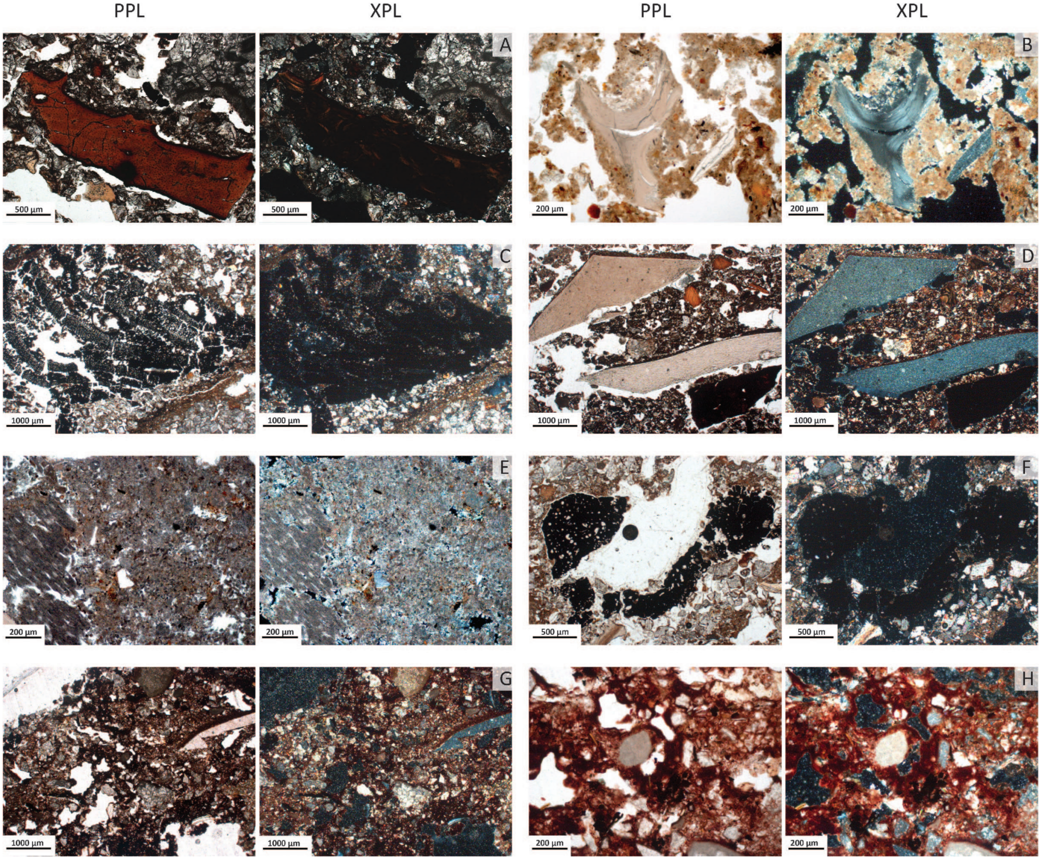

***Fig. 1* - Anthropogenic components, both in PPL (left) and XPL (right). (A) Burnt bone fragments (MM12, A9_SXII). (B) Calcine bone with embedded in a groundmass rich in calcite deriving from weathered ash (RF-19-31, A10IV_SVIII). (C) Charcoal fragment (MM13, A2 S16). (D) Micro-debitage flakes of microcrystalline chert. Note the sharp boundaries (RF-19-31, A10IV_SVIII). (E) Ash oxalate pseudomorphs resulting of the burning of calcium oxalate crystals from plants (RF-19-31, A10IV_SVIII). (F) Fat-derived char (MM49, A6_SXIV). (G) and (H) Ochre (MM22, A2 S21).**

as ochre (Figs. 1G, 1H). In Fumane, previous analysis (Cavallo et al. 2016) indicates the local origin for this mineral, likely in the surroundings of the site. This is in only one feature from unit A2 (S21) and in A2R, where appears as small-rounded aggregates but also spread in the matrix and part of the pedofeatures (such as coatings and external hypocoatings).

Organic petrology results

Organic petrographic analysis reveals a diverse range of organic matter types present in the anthropogenic features at Fumane. The selected samples come from three Mousterian units (A10, A9, A6). All of them preserved at least one micro-unit rich in organic matter and burnt material, which was the main focus of the petrographic analysis. From A10IV, we chose feature SVIII (TS RF-19-31), a stratified feature with five micro-units in thin section (Fig. 6A) between alternating ash-rich and organic matter-rich micro-units. In RF-19-31 (A10IV_SVIII), the upper black layer is rich in organic matter represented exclusively by fibrous charcoal

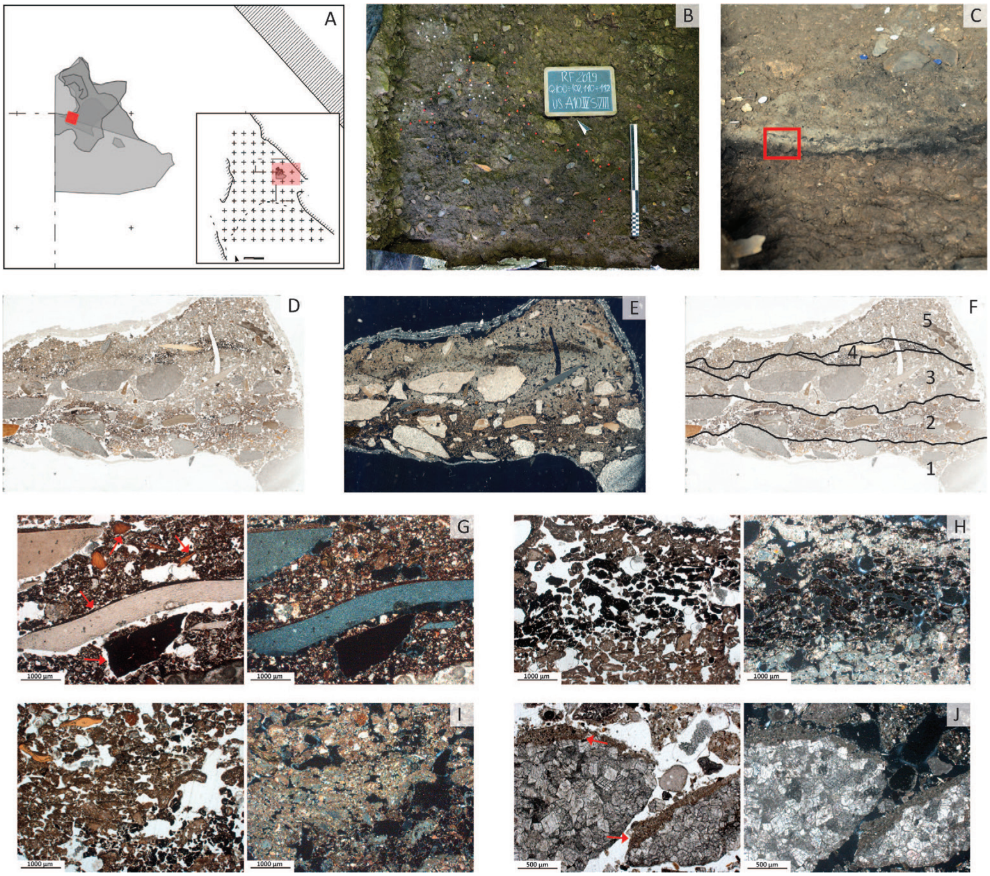

Fig. 2 - *(A) Location of the feature A10IV_SVIII and sample RF-19-31 (red squares). (B) and (C) Field photos in top view and profile. The feature's profile exhibits alternating sub-layers (grey and black), detectable in thin section. (D), (E) and (F) Thin section scans (RF-19-31) in PPL, XPL, and micro-unit subdivision. The thin section indicates five micro-units with mainly abrupt interfaces. (1) is comparable to the A10 sediment outside of the features: light brown colour, crystallitic b-fabric (calcite), single space porphyric c/f related distribution, and a complex microstructure (vughy-channel). (2) and (4) are rich in organic matter, with (2) preserving a higher content of anthropogenic material (arrows) (G). Both have a black colour with a crystallitic b-fabric (2) or mainly undifferentiated b-fabric (4) (H). (3) and (5) are rich in ash and plant material The micromass appears grey with a crystallitic b-fabric (calcite) (I). The c/f limit is at 20 µm (very fine sand), and the c/f related distribution is single-spaced porphyric. Micro-units (3) and (5) have a complex microstructure, often spongy-granular (H) and (I) and in few areas slightly lenticular. Common voids along the thin section are vughs, channels, compound packing voids and lenses. Pedofeatures include thin silty nonlaminated cappings (arrows), with ash as the main component in microunit 3 and 5 (J) and dusty microlaminated cappings and link cappings (mainly in microunits 1 and 2).*

tissues (fusinite) (Figs. 6A2, 6A3), which probably derive from herbaceous plants. The size of the tissues varies from about 50 µm to more than 300 µm. However, it was not possible to measure the tissue reflectance due to the tenuousness of the cell walls smaller than 2 µm (the measuring diaphragm has a diameter of 2 µm, so the particle to be measured must have a diameter of

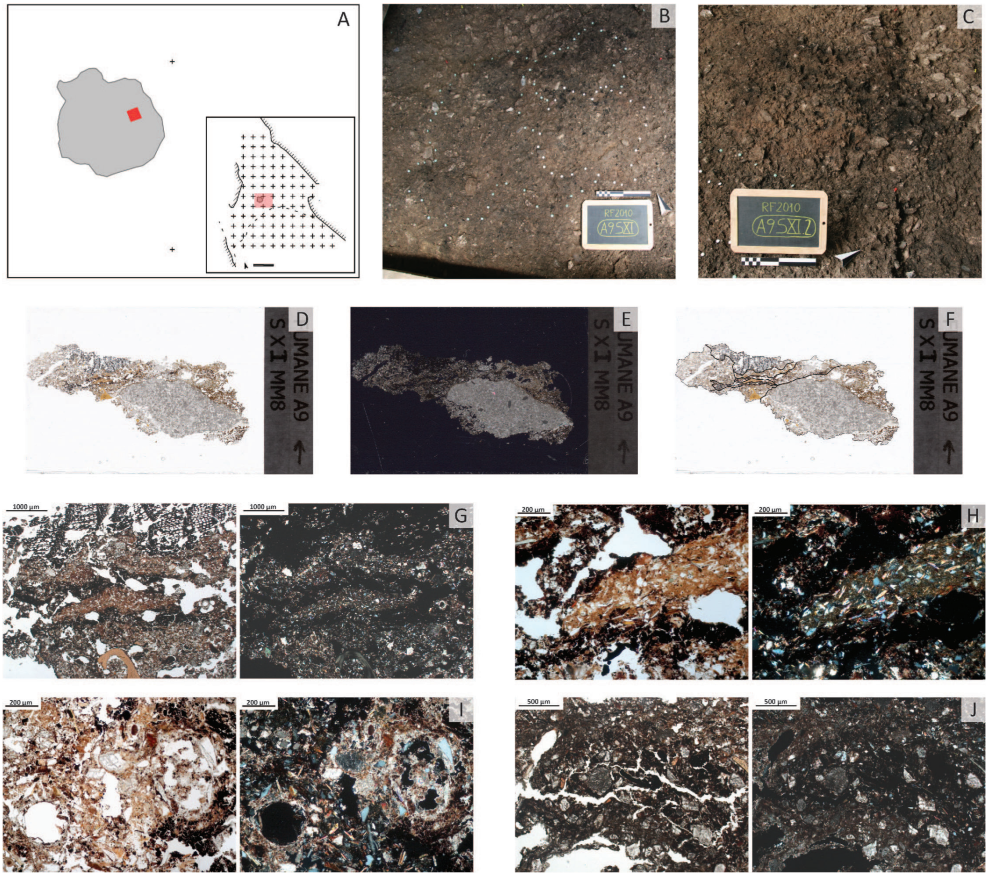

***Fig. 3** - (A) Location of the feature A9_SXI and sample MM8 (red square). (B) and (C) Field photos in top view and profile. (D), (E) and (F) Thin section scans (MM8) in PPL, XPL, and micro-unit subdivision. The groundmass exhibits a close porphyric c/f-related distribution, with the geogenic coarse fraction composed mainly of dolomite sand, very fine-fine sand quartz grain, and mica. The b-fabric is generally crystallitic, characterized by small birefringent of calcite. Except for the units rich in organic matter where there is an undifferentiated b-fabric. The thin section preserves several micro-units (3 different areas detected). Pay particular attention to the micro-units in the centre (area 2) characterized by the alternation of micro-units (G) rich in clay and mica and micro-units rich in organic matter. The first has an orange colour, a crystallitic b-fabric (mica and quartz), a close porphyric c/f related distribution and a massive microstructure (G) and (H). It preserves mica, quartz grains, calcite sand, organic matter and charcoals. Instead, the micro-units rich in organic matter have a black colour, an undifferentiated b-fabric, a close porphyric c/f related distribution, and a massive-vesicular microstructure. Its main component is organic matter and very few mica, quartz, and calcite sand (G) and (H). The lateral areas of the thin section show a dark brown colour, crystallitic b-fabric (calcite), a massive microstructure with very few voids such as vughs, channels (I) and very few planes (on the right area) (J). The components include mica, quartz, calcite sand, limestone fragments, pure clay aggregates, bones, organic matter, coprolite, and charcoals.*

more than 3 µm). In contrast, the lower black layer is composed almost exclusively of charcoal derived from woody tissues (Figs. 6A5, 6A6) and rarely from herbaceous plants. The second sample comes from A9II_SXX (MM25) (Fig. 6B). We subdivide this feature into five micro-units. The top of the sample presents a lenticular unit that corresponds to a mass of wood-derived

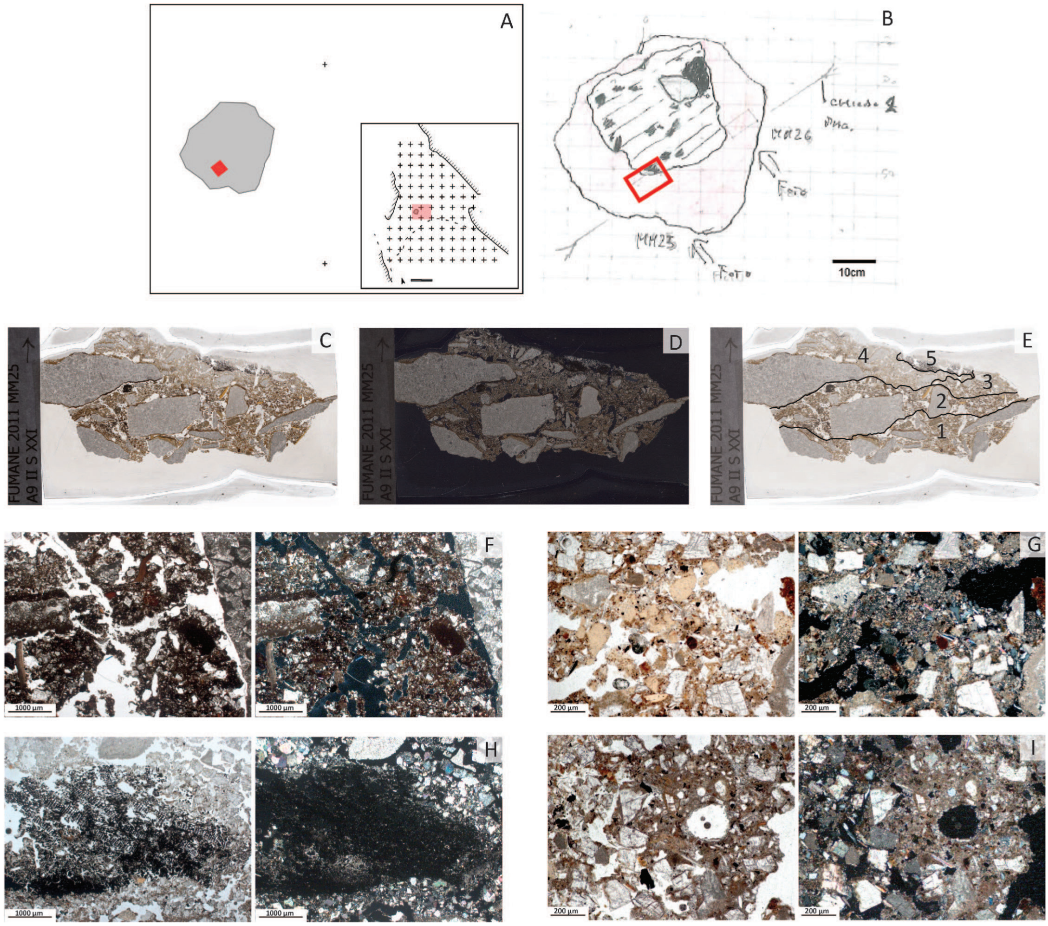

***Fig. 4** - (A) Location of the feature A9II_SXXI and sample MM25 (red square). (B) Report drawing. (C), (D), and (E) Thin section scans (MM25) in PPL, XPL, and micro-units subdivision. Voids are more or less homogeneous along the thin section, these are mainly vughs and channels, with very few vesicles. Micro-units (1), (3), and (4) have a brown-light brown colour, a crystallitic b-fabric (calcite), a close porphyric c/f related distribution, and a vughy microstructure. (2) preserves the similar characteristics of the previous micro-units (microstructure more complex vughy-channel) (F) but has a dark brown-blackish colour. It is a mix of geogenic, biogenic, and anthropogenic components, both burnt and unburnt (G). (5) has a black colour, an undifferentiated b-fabric, close porphyric c/f related distribution and a complex microstructure (vughy-channel) (H). It is rich in organic matter and charcoal fragments and has an abrupt interface with the lower unit. Pedofeatures are usually dusty microlaminated or nonlaminated cappings (micro-units 1, 2, 3, 4), external calcite hypocoatings (I) (micro-unit 4), and calcite infillings (micro-unit 5).*

charcoal tissues (Figs. 6B2, 6B3). The tissues, whose size ranges from 300 to 400 µm, are mixed with numerous smaller tissue fragments (cell walls) whose size is smaller than 50 µm and appear light grey in reflected white light. Their reflectance varies from 0.60 to 1.34 %Ro with a mean of 0.86 %Ro (see reflectance histogram supplementary material), classifying them as low reflecting fusinite (semifusinite). This interval of reflectance indicates formation temperatures

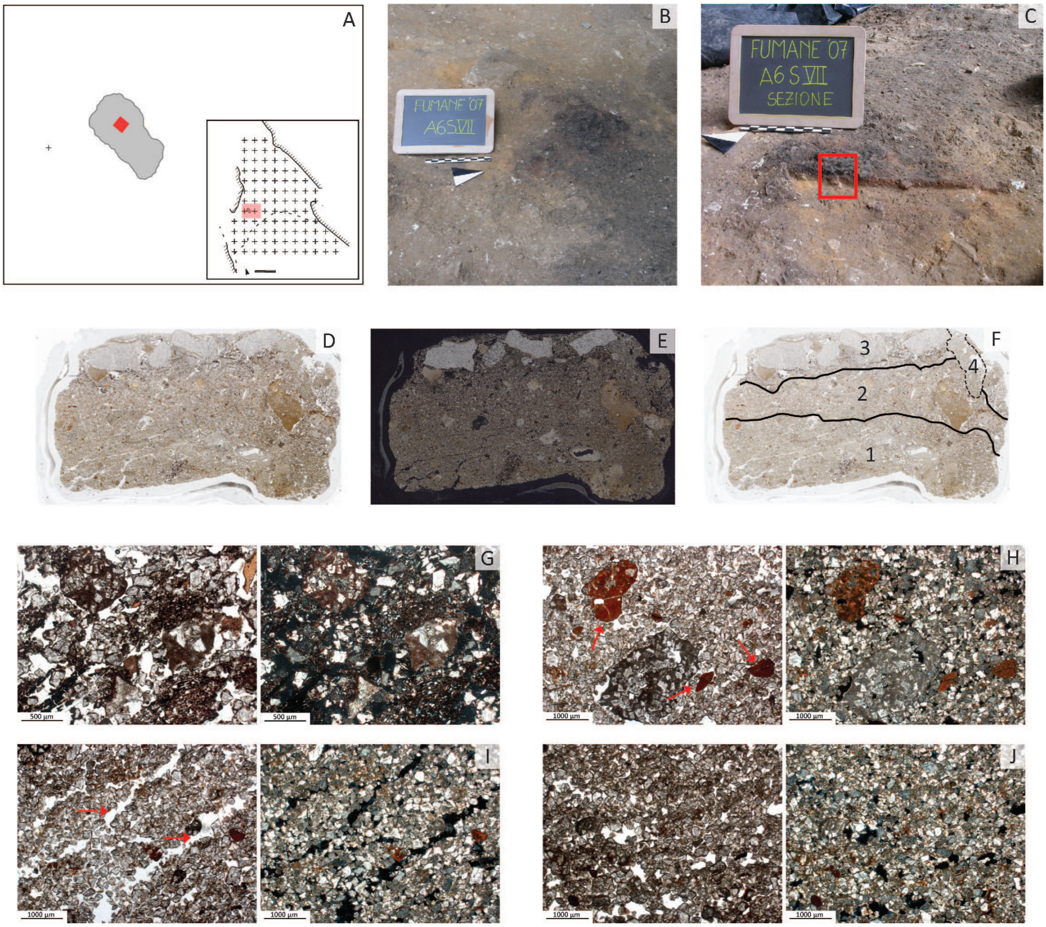

***Fig. 5** - (A) Location of the feature A6_SVII and sample MM34 (red square). (B) and (C) Field photos in top view and profile. (D), (E), and (F) Thin section scans (MM34) in PPL, XPL, and micro-unit subdivision. Note that the thin section includes three different micro-units (the 4 is a borrow). The upper one (3) is identifiable from the high content of organic matter, charcoals, and burnt materials (G). It has a dark brown-black colour, a crystallitic b-fabric (calcite), a single-spaced porphyric related distribution. The predominance of vughs gives the micro-unit a vughy microstructure. The lowers (1 and 2) differ from each other only from the colour change of the clay aggregates (arrows) (H), light orange (1) to dark orange (2). Both show a crystallitic b-fabric (calcite) and a chitonic c/f related distribution. Both have a complex microstructure. (1) is vughy-lenticular-subangular blocky (I), characterized by lenses and planar voids (arrows), rather than the (2) with a vughy microstructure with a lenticular area within the left side (J). The main pedofeatures are dusty clay nonlaminated cappings and link cappings.*

approximating 254°C to 340°C (Jones and Lim, 2000). This temperature range is also characteristic of the other samples analysed when the cell size allowed the measurement. These are strongly fragmented, and usually, the particle's size varies from 40 to 200 µm. Fat-derived char particles (Fig. 6B6) were detected too, with a different abundance and homogeneity within the micro-unit in the middle of the thin section. A6_SII (MM31) is the third feature that we analysed using organic petrology. The thin section shows four micro-units (Fig. 6C). The top micro-unit

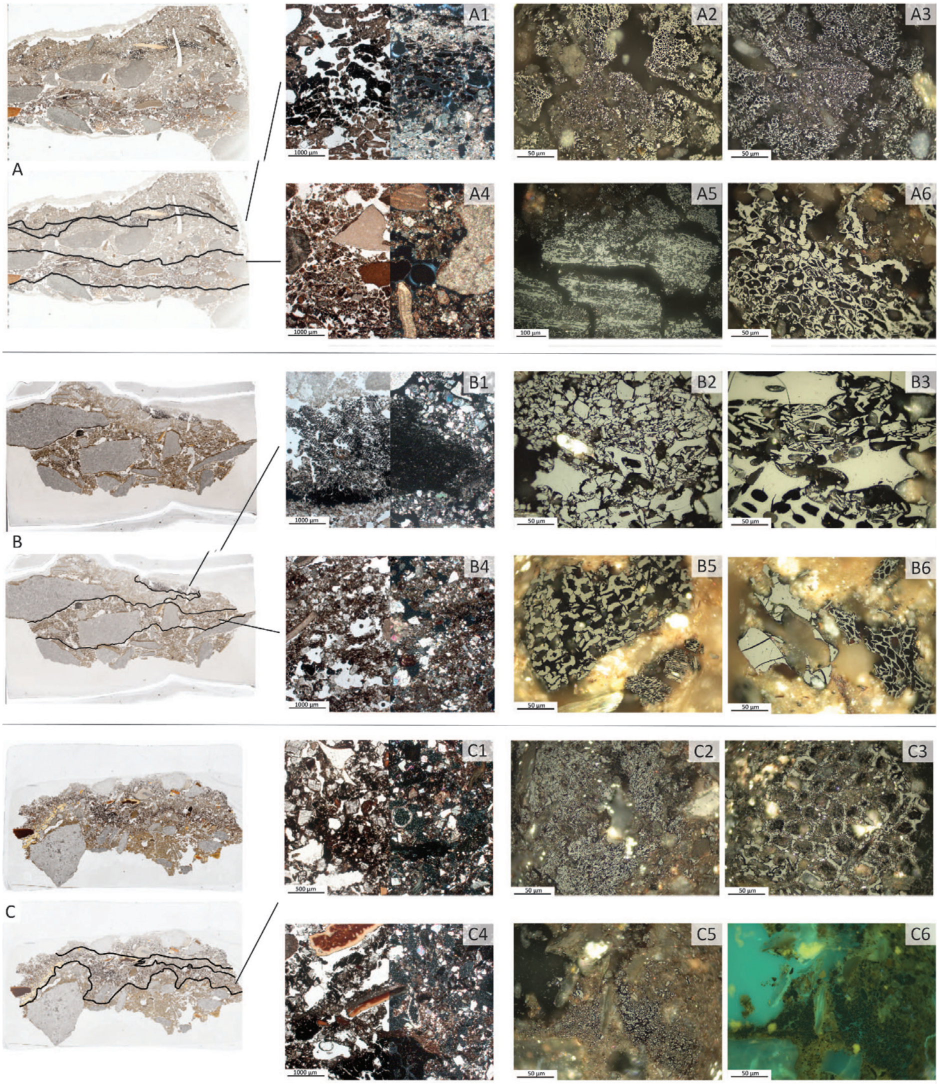

***Fig. 6** - Organic petrology analysis (incident white light, oil immersion) of samples RF-19-31, MM25, MM31. (A) RF-19-3 form A10 SVIII. (A1) and (A4) Micromorphological overview of the upper and lower organic layer (PPL and XPL). (A2) and (A3) Detail of collapsed tiny herbaceous-derived charcoal tissues. (A5) Burnt partly humified woody tissue. (A6) Burnt partly humified woody tissue showing droplets of humic gels. (B) MM25 from A9 SXXI. (B1) and (B4) Micromorphological overview of the upper and lower organic layer (PPL and XPL). (B2) and (B3) In situ crushed wood-derived charcoal (B5) Burnt and fragmented partly humified wood tissue. (B6) Fragmented fat-derived char particle (on the left) and fragments of wood-derived charcoal (on the right). (C) MM31 form A10 SII. (C1) and (C4) Micromorphological overview of the black organic layer in the centre (PPL and XPL). (C2) In situ crushed tiny tissues of fusinite, partly replaced by phosphates. (C3) Strongly fissured wood-derived charcoal, partly replaced by phosphates. (C5) In situ crushed fusinite, partly replaced by phosphates. (C6) The same field of view of (C5), but in incident light fluorescent mode, oil immersion. Note the fluorescent rounded mineral aggregates are rich in phosphates and charcoal fragments embedded in phosphate-rich matrix.*

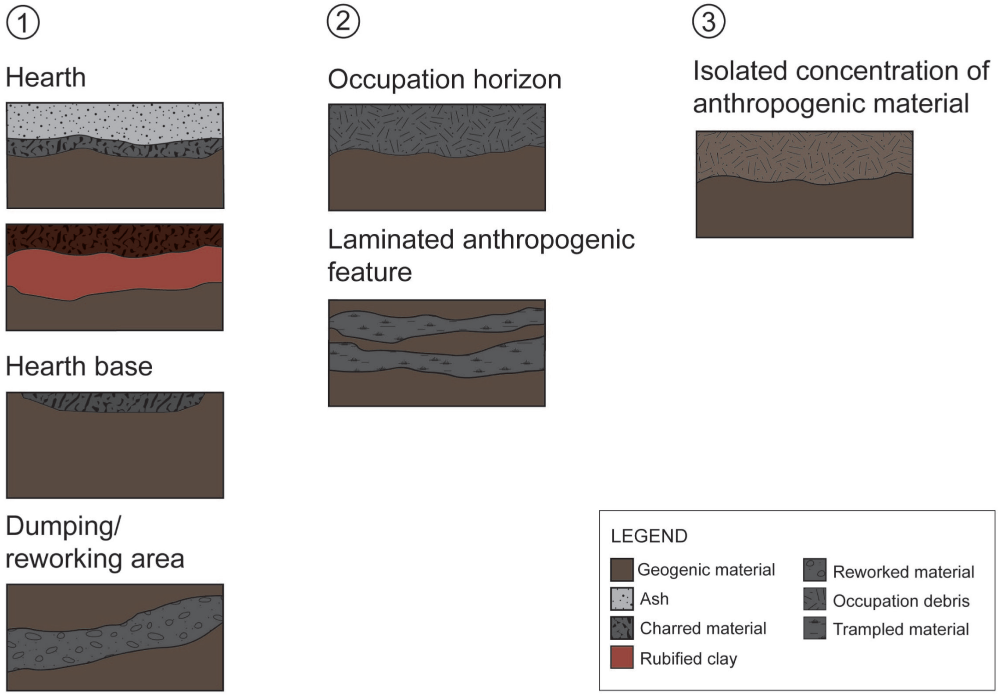

Fig. 7** - **Micromorphological classification system. (1) Shorter-term event group, Hearths, hearths base, and dumping/reworked area. (2) longer-term event group. Occupation horizon and laminated anthropogenic feature. (3) Isolated concentration of anthropogenic material.

is rich in organic matter composed of charcoal (woody tissues). The black micro-unit in the middle of the thin section (under an ash micro-unit) has charcoal both from wood and herbaceous plants (Figs. 6C2, 6C3) but also a high frequency of bone fragments and very few particles of fat-derived char.

In all three samples analysed with organic petrology, we note that all of the vegetal tissues display evidence of having undergone humification prior to burning. They show droplets of humic gels attached to swollen cell walls (Braadbaart and Poole, 2008; Braadbaart et al. 2012; Villagrain et al. 2017b) (Figs. 6A5, 6A6). Moreover, charcoal tissues originating from wood and herbaceous plants are either strongly fissured or crushed in situ. They keep their original structure, and frequently phosphates fill their cell cavities (especially in sample MM31) (Figs. 6C5, 6C6). Further, numerous charcoal tissues display corrosion, and often secondary carbonates (calcite) fill the spaces between the broken cell walls.

Discussion

Micromorphological classification system of features

In total we analysed 86 thin sections from 59 anthropogenic features at Fumane (4 thin sections analysed in this study did not come from anthropogenic features), spanning across 8 units including the Mousterian (A10, A9, A6, A5, and A4), the Uluzzian (A3), the Protoaurignacian (A2) and late Protoaurignacian (layer D3bAlpha). In order to identify both spatial and diachronic trends in the occurrence of the features, we decided to employ a classification system (Tables supplementary information).

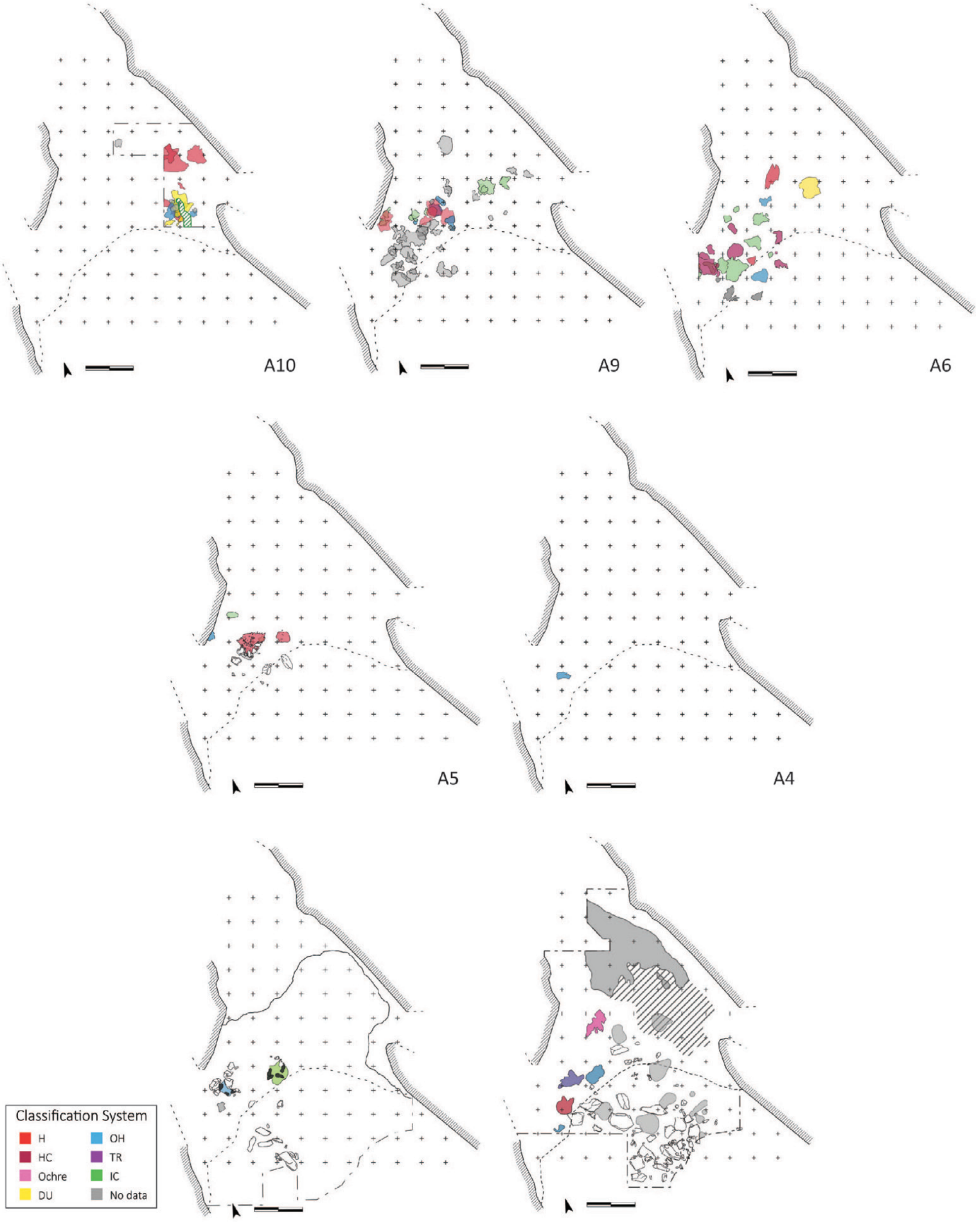

***Fig. 8** - Site maps of Fumane Cave showing the spatial distribution of the features by layers (A10, A9, A6, A5, A4, A3, and A2). Hearth (H) in red; hearth with change in clay colour (HC) in burgundy; ochre feature in pink; dumping/reworking area (DU) in yellow; occupation horizon (OH) in blue; laminated anthropogenic feature (TR) in violet; isolated concentration of anthropogenic material (IC) green; and feature with no data (not sampled or without a thin section) in grey. The dark green area with line filling pattern identifies a borrow.*

Although we do not follow a strict microfacies analysis in this study (e.g., Courty 2001; Goldberg et al. 2009; Haaland et al. 2020; Karkanas et al. 2015; Miller et al. 2013), by classifying the anthropogenic features based on their microscopic characteristics we are broadly employing a facies concept which allows us to link shared depositional characteristics with an interpretation of human activities (Villagran et al. 2017b). All detailed information on each category is summarised in Tables 1 and 2 and Figure 7. Thus, the classification system developed for the features at Fumane both simplifies the spatial and diachronic analysis and also allows us to make genetic interpretations of the various types of anthropogenic features.

In general, the anthropogenic features at Fumane can be sorted into three groups that relate to the anthropogenic activities responsible for their formation and that generally correspond to their degree of resolution. The first (Tab. 1) includes relatively high-resolution, shorter-term events, such as a single episode or action that took place within the cave and includes features that we interpret as hearths or dumping/reworking areas. The second group (Tab. 2) consists of lower-resolution, longer term events, characterized by the development of a surface that likely formed as a result of trampling. Within this group, it is possible to distinguish between 1) laminated features resembling "trample" deposits as described by Banerjea et al. (2015) and 2) a more homogeneous surface we called occupation horizons. A third category (Tab. 2), more difficult to define precisely, consists of isolated concentrations of anthropogenic material. It includes all those features which, on analysis of thin sections, show similar characteristics to each other, and do not fall within the types of the first and second groups.

Fuel selection strategies

The lack of complexity in the structure of the Middle Paleolithic combustion features does not imply a lack of complex behaviour by Neanderthals. The combination of micromorphology with organic petrographic analysis demonstrates diversity in the range of Neanderthal's fire-related behaviours. We identified three different types of fuel (Fig. 6) within the hearth bases examined from A10, A9, and A6 (Late Mousterian). We noted only herbaceous tissues in RF-19-31 hearth base (A10IV_SVIII), only woody tissues in MM25 (A9_SXXI) and a mix of wood, herbaceous and bones in MM31 (A6_SII). Firstly, these observations highlight the preference of plant material over bones for fire-making. Secondly, by identifying three Neanderthal hearths directly stacked on top of one another, with three different fuel compositions, we argue for some differentiation of Neanderthal's fire and fuel selection strategies. Previous analysis of charcoal remains recovered from two of these units (A9 and A6) (Basile et al. 2014; Peresani et al. 2011a, 2013) does not suggest an adaptation to drastically different ecological contexts that would have led the groups to choose a woody fuel instead of a mix of wood, grass, and bones, as suggested in other archaeological contexts (e.g., Hohle Fels Cave, Miller 2015). Additionally, the ecological context of A6 does not imply a scarcity of wood that may have encouraged the use of bone (Théry-Parisot et al. 2002).

Interestingly, humified organic matter was identified in all studied combustion features from the Middle Paleolithic. Humified wood burns poorly and incompletely compared to dry wood, and therefore may appear as the dominant residue in combustion features regardless of the original composition of the fuel, making it difficult to quantify a selective use of partially humified wood (Théry-Parisot et al. 2010). However, the presence of partially humified material in all the analysed hearths implies that humified material formed at least part of the fuel used by Neanderthals to light their fires. The presence of humified plant material in the hearths suggests that Neanderthals probably collected their fuel either at the edge of a river or from surroundings in the undergrowth. While the collection of humified material may represent an expedient strategy, it is also possible that the harvesting of decayed plant material may indicate a specific choice due to its particular characteristics during combustion, such as reduction of combustion time or a need for less intensive fuel management; additionally, selection of humified plant material can also allow for a greater extension of the supply area for fuel (Théry-Parisot 2006). The identification of humified plant material in some of the Middle Paleolithic combustion features at Fumane can be useful for assessing the use of the site (e.g., Théry-Parisot et al. 2005; Théry-Parisot 2006). As Théry-Parisot (2006) has argued, the selection of decayed wood suggests that the groups were highly mobile and that they used the sites for short-term occupation Collection of degraded wood by Neanderthals was also inferred from taphonomic evidence at de Nadale Cave, a context situated east of Fumane and dated to the beginning of MIS4 (Vidal-Matutano et al. 2022).

Spatial distribution and occupational intensity

A microcontextual analysis combined with the development of a classification system provides evidence for a greater diversity of activities and behaviours beyond simple burning inside Fumane. Here we were able to interpret the anthropogenic features as representing hearths, dumping areas, laminated “trample”, and occupation horizons.

The identification of different feature types and their spatial distribution can be related to other spatial archaeological data. Recent studies (Fiore et al. 2016; Martellotta et al. 2020) from A9 revealed that faunal remains and retouchers mainly occur where there are fewer combustion features (north-eastern sector of the cave in the proximity of the left wall), suggesting the existence of distinct areas for production activities, prey exploitation, combustion, and waste. Further, the number of features present tracks with general trends in the density of lithic and faunal materials, possibly correlating with changes in site occupation and use. Peresani et al. (2011b) showed that the accumulation of faunal remains and lithic artefacts shifts from intense and persistent (A6) to more ephemeral (A5), a pattern we also observe with the anthropogenic features (18 in A6 and 5 in A5). In fact, the number of artifacts seems to follow the pattern seen with the number of features (Fig. 8), suggesting a strong link between the anthropogenic features and the amount of the archaeological material (such as bones and lithic artefacts). Looking simply at the number of features (Fig. 8), within the entire atrial area excavated, what we observe is a decreasing trend through the Mousterian (from A10 to A4). Within the Uluzzian (A3) and Protoaurignacian (A2), the number rises again with a substantial number (21 features) in A2. The late Protoaurignacian (D3balpha), however, is only represented by one anthropogenic feature.

What we do not see at Fumane is a diachronic change in the types of human activities, an observation that stands in contrast to similar micromorphological studies of sites from Middle Stone Age contexts in South Africa (Goldberg et al. 2009; Haaland et al. 2020; Karkanas et al. 2015; Miller et al. 2013; Wadley et al. 2011). From the Middle to the Upper Paleolithic the activities that formed the features are the same (hearth burning, dumping, trampling, etc.). However, what does appear to change is the complexity of the activities that resulted in the formation of the features. In the Middle Paleolithic, the vast majority of features formed from a single activity and therefore a single feature can fall under one of our classification groups. We note only two exceptions to this observation: A5_SIII and A10IV_SVIII. The first, A5_SIII (Supplementary Materials A4), has considerable size (100 cm of diameter and 10-15 cm of depth), a half-circle of boulders surrounded it, and it has several sublayers (Peresani et al. 2011a), all of which implies that this features likely represents the centre of the site’s activities. This feature is very unusual for the Middle Paleolithic of Europe, considering that intact combustion features from Middle Paleolithic contexts are usually flat, and only a few cases exhibit a basin shape or are delimitated by stones (Leierer et al. 2020). The second complex feature from the Middle Paleolithic at Fumane is A10IV_SVIII (Fig. 2), which preserves a structure composed of

6 sublayers, with alternation of both ash layers and organic-rich layers. Despite these two exceptions, compared to the Middle Paleolithic combustion features, those from the Upper Paleolithic appear more complex and more stratified. Within unit A2 (Protoaurignacian), the features analysed are micro-stratified and record different activities in palimpsest within the same feature (e. g. intact combustion feature and scatter). Feature S16, for instance, preserves both an occupation horizon and an isolated concentration. Feature S17 is a hearth with trampling evidence nearby; meanwhile, Feature S20 includes both an occupation horizon and laminated anthropogenic deposits.

Occupation horizons have often been used in comparison to intact hearths and other anthropogenic features to infer the frequentation pattern of the site and its duration. In particular, as previously suggested and demonstrated by Karkanas et al. (2015) and others (Goldberg et al. 2009; Haaland et al. 2020; Miller et al. 2013; Wadley et al. 2011), intact hearths often correlate with a pattern of site use dominated by shorter visits. In contrast, thicker (usually more reworked) anthropogenic horizons and burned deposits suggest more intensive use of the site. They are reminiscent of a prolonged period of occupation, showing the overlapping of human activities. At Fumane, we do not have thick and laterally extensive anthropogenic horizons, but rather thin (3 to 5 cm) and limited patches. Since post-depositional alteration has only partially impacted their preservation (Kehl et al. in prep.), it is likely that they are directly related to human presence at the site. Therefore, we are inclined to think that these thin and limited patches are linked to the intensive use of the site but, given their characteristics more likely to short but repeated frequentations.

In general, the diachronic change in the frequency, but not type, of features at Fumane may suggest that these changes do not so much reflect a shift in the site-use patterning but rather are more related to changes in mobility strategies, since this shift coincides with the disappearance of Neanderthals and the arrival of modern humans in the region. In addition, we would suggest that the variation in feature complexity and the connection to occupation horizons between the Middle and Upper Palaeolithic may reflect variation in the duration of site use. With 'simpler' features contrasting with the occupation horizon, the Middle Palaeolithic appears characterised by short-term but frequent cave use for the lower units. The features seem to decrease as we approach the Uluzzian, hinting that human groups frequented the site less and less or more sporadically. This trend sees a reversal with the Protoaurignacian. Although the features appear more complex, and the site-use pattern itself appears to be more organised, suggesting longer-term occupation in the Upper Palaeolithic.

Several studies have used the accumulation of sediments and cultural material as a proxy for palaeodemography. Estimates of the density of a specific class of cultural material or the dietary value of any faunal remains recovered at a cave should reveal a positive correlation with the occupational intensity of a site. Thus, we can use the accumulation rates of hearths, stone tools and bones, albeit influenced by a range of local environmental, economic and social factors (see French 2016 for review), to infer variations in occupation intensities with, on a larger scale, increases or decreases in population densities. Estimations about Neanderthal and early Homo sapiens changing population numbers in Europe seem to reveal an increase in favour of the latter (Malleras and French 2011; Conard et al. 2006, 2012). However, these studies do not provide clues about the demographic dynamics of these local natives before and at the dawn of their demise. Models built on an ensemble of proxies indicate that the disappearance of Neanderthals might be related to the small size of their population, which caused them to cross a critical biological threshold for the population's persistence (Vaesen et al. 2019; Kolodny and Feldman 2017). Thus, the demise of the Neanderthals could have been caused by inbreeding, Allee effects and stochasticity even in the absence of competition with modern humans (ibid.). Internal, demographic dynamics of Neanderthal populations leading to shrinking population densities could be reflected in the distribution of the archaeological record, producing ephemeral signatures of human occupation of caves, shelters, open-air sites and of whole territories previously inhabited for a long time and in a variety of ways. Currently, the decrease in the number of hearths at Fumane corresponding with the disappearance of the Neanderthals encourages further investigation. Additional data on the density of archaeological remains across units A11 to A4 combined with age models and sedimentation rates will be crucial for examining population trends over time.

Conclusions

In this study, we investigated the anthropogenic features through a macro- and micro-contextual approach. We started with a field description analysis to which we added micromorphology and organic petrology. By starting with the field reports, we wanted to highlight the importance of standardized field observations and sampling procedures, which are the basis of a multi-analytical approach. On the other hand, the use of micromorphology and organic petrology allowed us to build a solid and systematic classification for describing anthropogenic evidence. This system proved to be fundamental to understand the nature of the features and trace changes and patterns within the human occupation at Fumane.

With our results, we were able to highlight the considerable variety in number and types of the features, providing new information on the nature of the human activities at the site, the intensity of the occupation, and behavioural patterns. We suggested that the human activities do not change diachronically within the site. What changes is the complexity of the feature itself between the Neanderthal and Homo sapiens occupants. This likely indicates variation within the duration of the cave occupation, with modern humans likely using the site more intensively and for longer periods of time compared to the Neanderthals. By applying organic petrological analyses to the micromorphological samples, we were able to document variation in the fuel selected for burning in the Middle Paleolithic and also identify the presence of humified plant material within the Middle Paleolithic combustion features. These results suggest that the fuel selection strategies of Neanderthals at Fumane were flexible and likely coupled with other strategies as part of a highly mobile settlement system.

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Authors' contributions

M.P., D.M., C.E.M., and N.J.C. designed the research, M.P., R.D. and D.M., provided field descriptions of the anthropogenic features, D.M. performed micromorphological analyses and B.L. organic petrology analyses, D.M. wrote the manuscript with contributions of all authors.

Conflicts of interests

The authors declare that there are no conflicts of interests.

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Appendix II

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ORIGINAL PAPER

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

Diana Marcazzan[1] · **Christopher E. Miller**[1,2,3] · **Nicholas J. Conard**[2,4]

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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

[1] Institute for Archaeological Sciences, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany

[2] Senckenberg Centre for Human Evolution and Palaeoenvironment, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany

[3] SFF Centre for Early Sapiens Behaviour (SapienCE), University of Bergen, Post Box 7805, 5020 Bergen, Norway

[4] 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 though 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 (Porraz 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 > 12m2 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 m2 (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

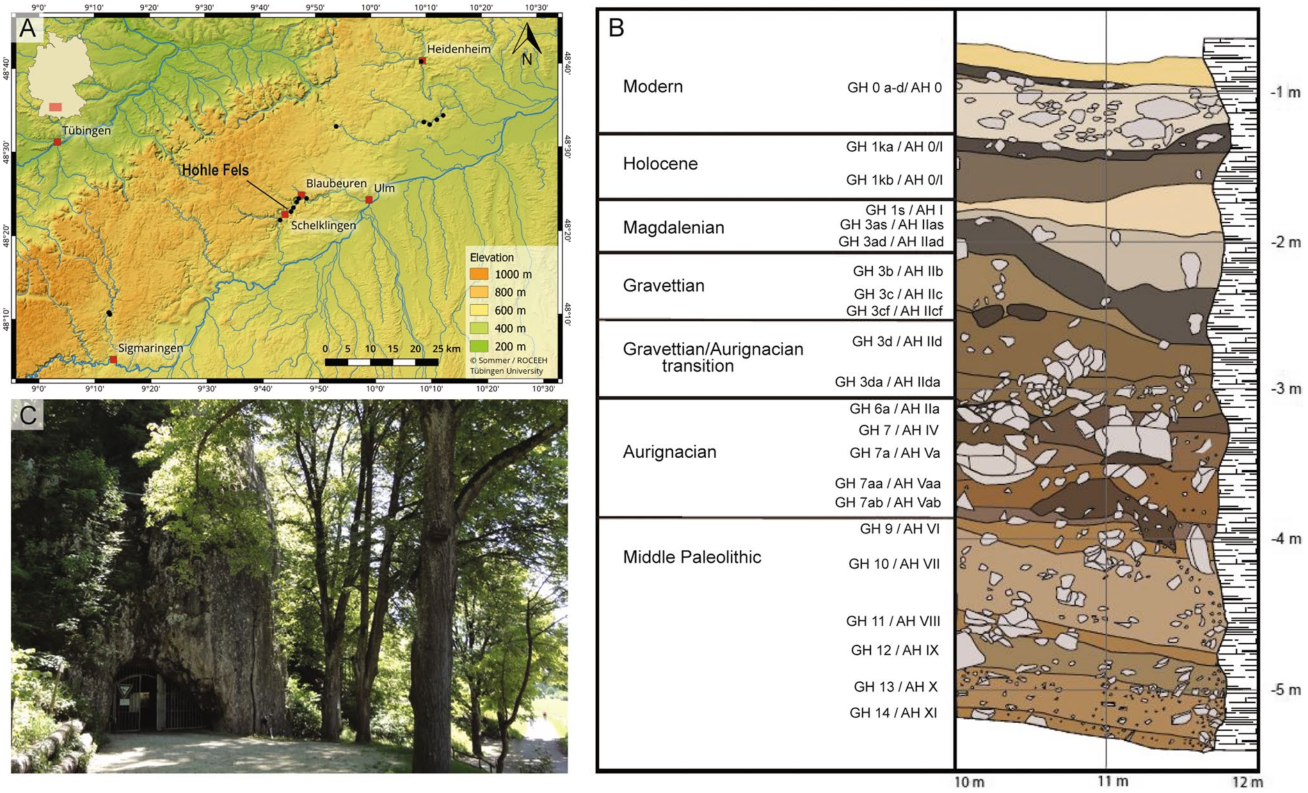


Fig. 1 Site location and stratigraphic sequence. **A** Map of the Swabian Jura of southwestern Germany with the location of Hohle Fels. Map courtesy of C. Sommer, University of Tübingen (https:// doi. org/ 10. 5281/ zenodo. 34,603 01). **B** Stratigraphic profile highlighting the cultural periods in 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; Karkanas 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 widespread 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

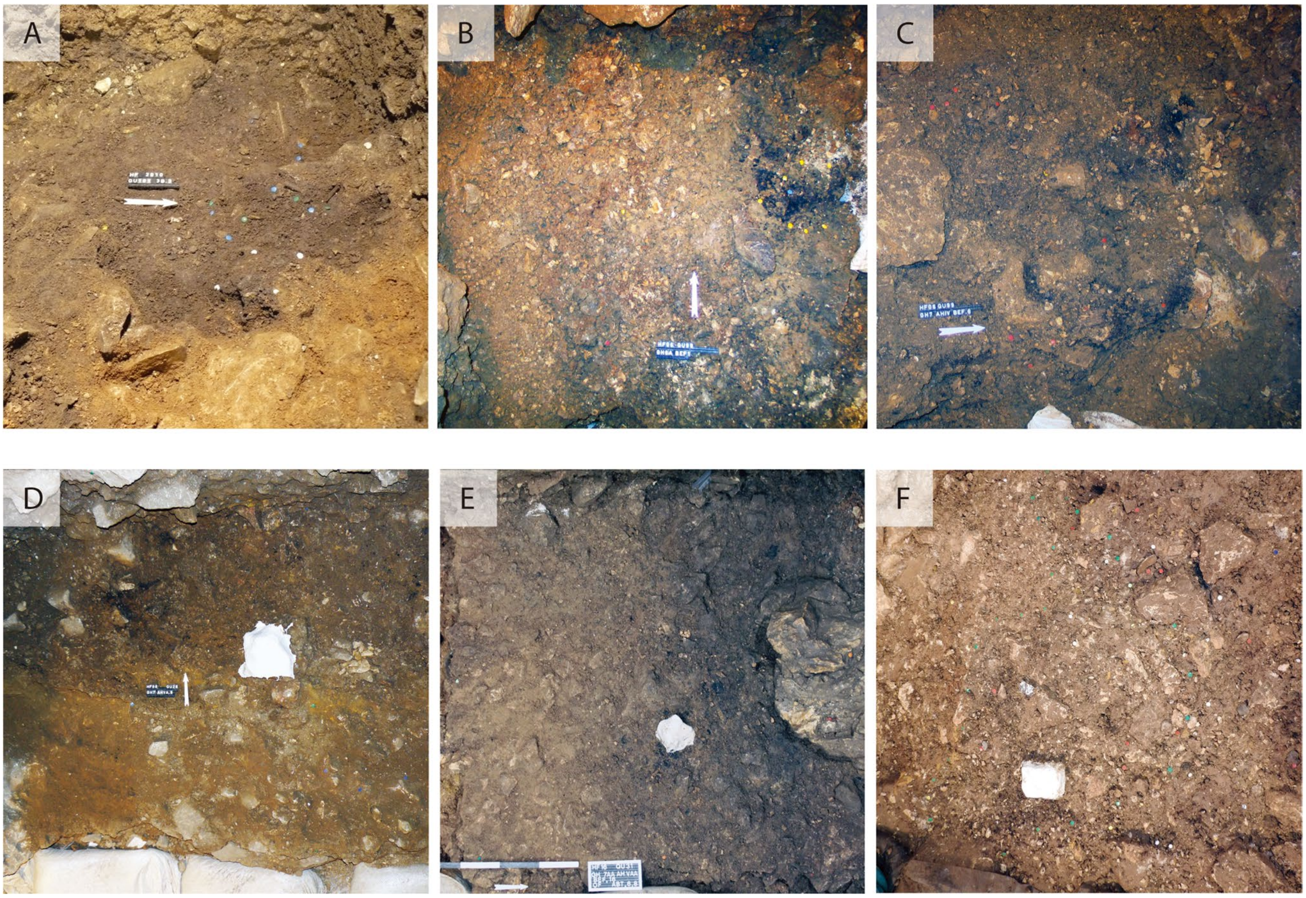


Fig. 2 Excavation pictures of the features from Hohle Fels. **A** GH 3b feature 3 (limit of the feature visible). **B** GH 6a feature 1. **C** GH 7 feature 6 (limit of the feature visible). **D** GH 7a feature 7 = 9; **E** GH 7aa feature 16; **F** GH 14 feature 1

the source for the dark colouration of bone fragments within the features. µXRF 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).

Results

Here we provide results from the micromorphological, µXRF 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			
GH_AH	Bone (> 3 cm)	Lithic (> 1 cm)	Total	ID	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

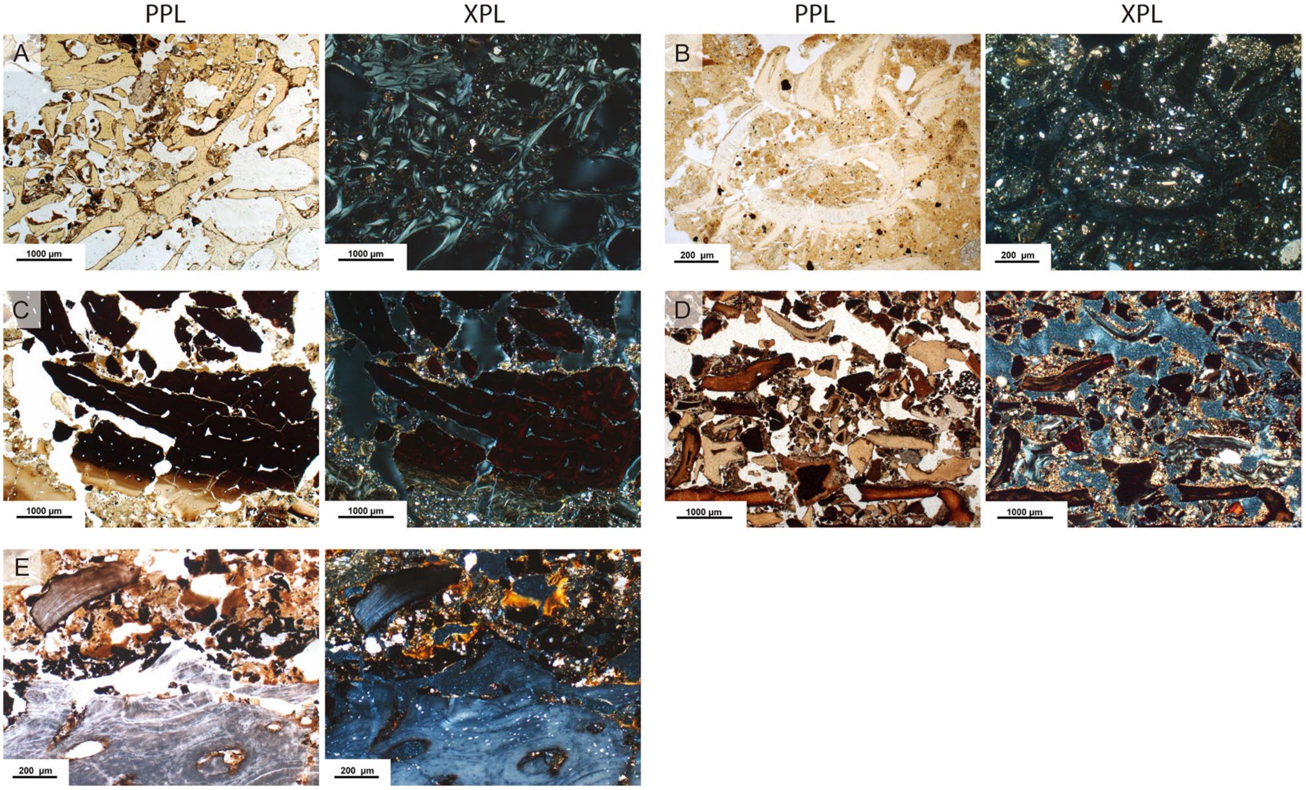


Fig. 3 Photomicrographs of the anthropogenic components, both in PPL and XPL. **A** In situ crashed fresh bone appearing light pale yellow/colourless in PPL and with a strong low-order interference colour (white, grey, black). **B** Fragmented fish vertebrae showing the typical rounded morphology. **C**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

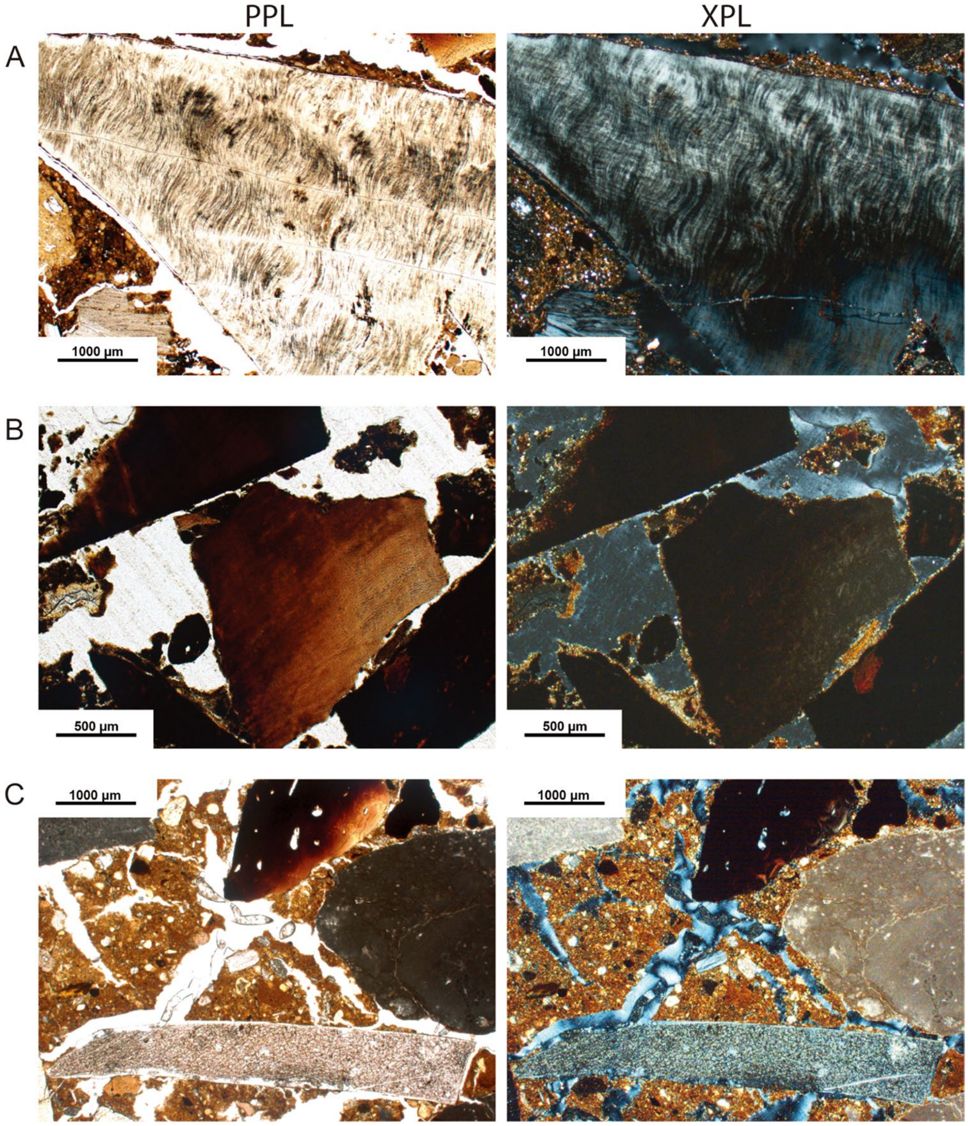


Fig. 4 Photomicrographs of the anthropogenic components, both in PPL and XPL. **A** Fragment of fresh ivory exhibiting bands like growth rings in PPL and a brown low-order grey of interference colour in XPL. **B** Charred fragments of ivory partially stained by Mn (see figure X for details on the micro-XRF 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 IIcf, 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

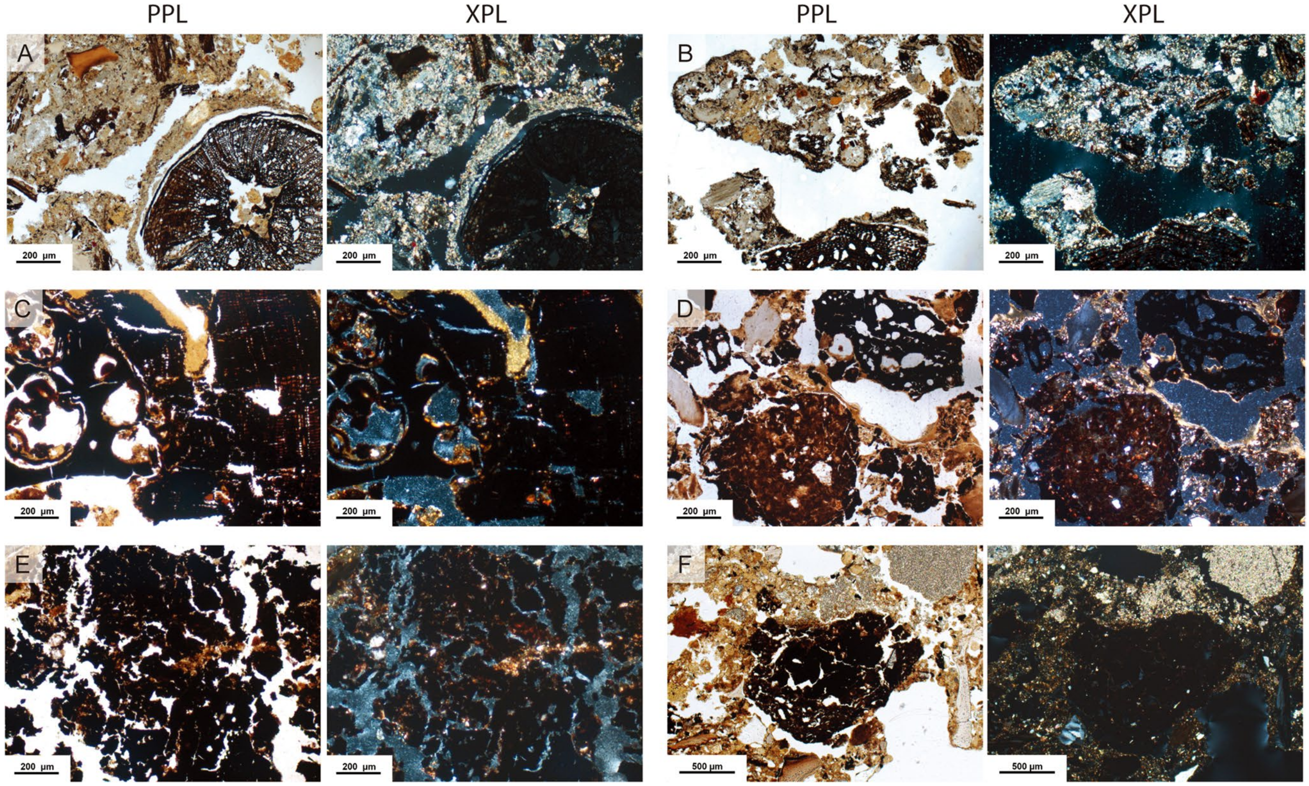


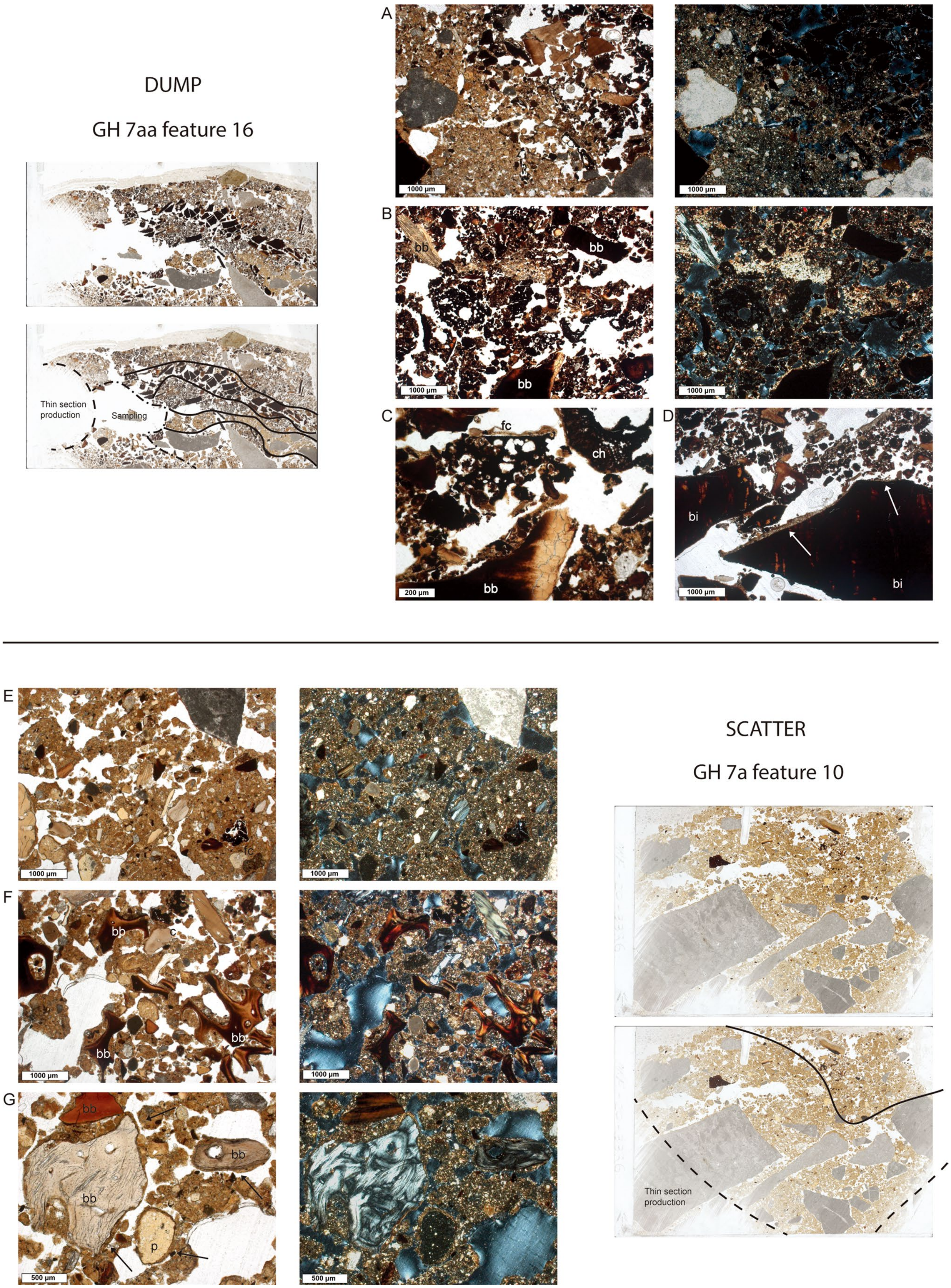
Fig. 5 Photomicrographs of the anthropogenic components, both in PPL and XPL. **A** and **B** Fragments of charcoal, appearing opaque both in PPL and XPL, embedded in altered ash. **C** Charcoal fragment and fat-derived char. **D**, **E** and **F** fat-derived char from the burning of flesh and fat.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


DUMP
GH 7aa feature 16
Thin section production
Sampling
A
1000 µm
1000 µm
B
bb
bb
bb
1000 µm
1000 µm
C
fc
ch
bb
200 µm
D
bi
bi
1000 µm
E
fc
1000 µm
1000 µm
F
bb
c
bb
bb
1000 µm
1000 µm
G
bb
bb
bb
p
500 µm
500 µm
SCATTER
GH 7a feature 10
Thin section production

◂**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 µXRF 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 ~ 300° (Table 4), while GH 7a and 7aa have a preferred orientation, with a dominant cluster facing southwest at ~ 210° (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 (~ 300°).

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°, while the plunge variance is 11.6°. 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

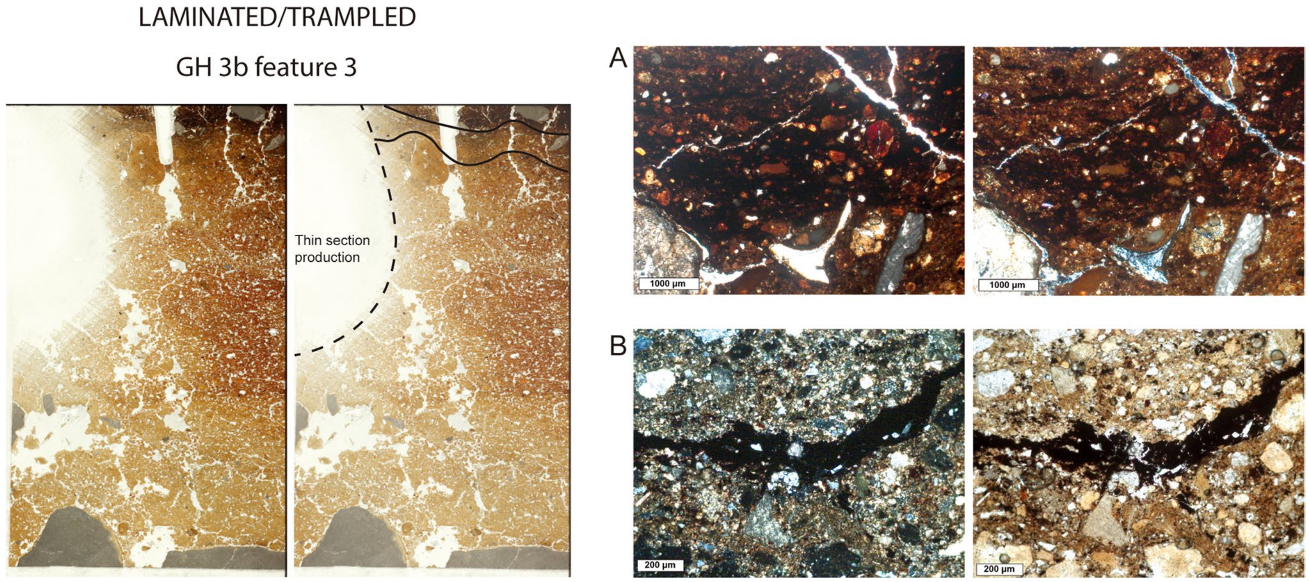


Fig. 7 Micromorphological characteristics of laminated/trampled feature from GH 3b feature 3 (HF-10–304). **A** Black groundmass showing lamination and a massive microstructure (PPL and XPL). **B** Charred material (PPL and XPL)

preferred orientation dipping in features 6 (GH 7) and 1 (GH 14) with a dominant cluster at ~ 280° (west) and features 7 (GH 7a) and 16 (GH 7aa) clusters at ~ 210° (southwest). 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° with considerable variance. In contrast, feature 1 from GH 14 preserves an average plunge angle equal to 11° (Table 5) and a plunge variance at 9°.

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).

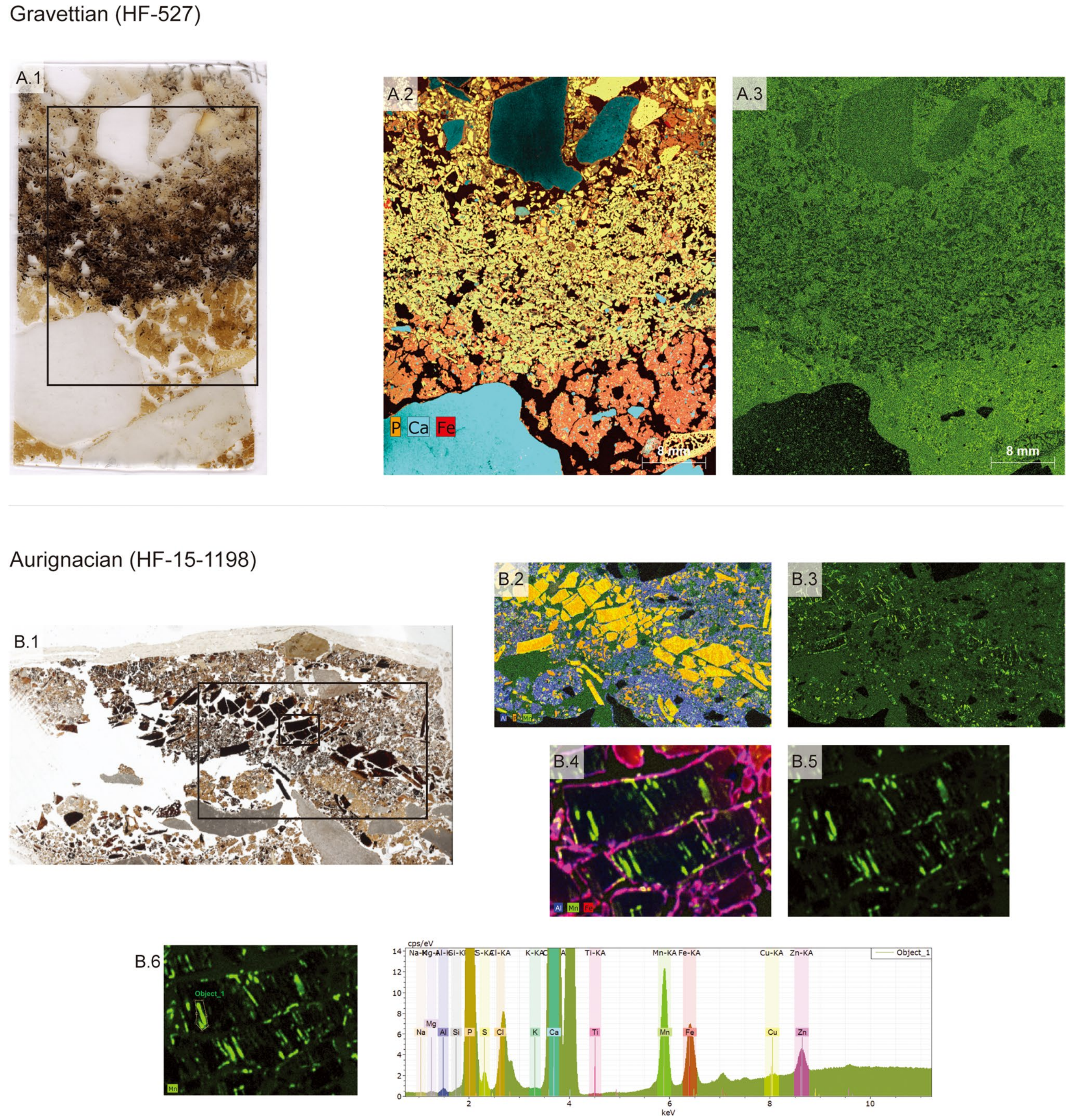


Fig. 8 (A.1) Scan of thin section HF-572 from the Gravettian layer GH 3cf AH IIcf. In (A.2) note the micro-X-ray fluorescence (XRF) elemental maps showing the spatial distribution of phosphate (P) in yellow, calcium (Ca) in light blue and iron (Fe) in red and in (A.3) the spatial distribution of manganese (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 aluminium (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 aluminium (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	*P* (Rayleigh)	Mean	Var	Mean res length	*P* (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

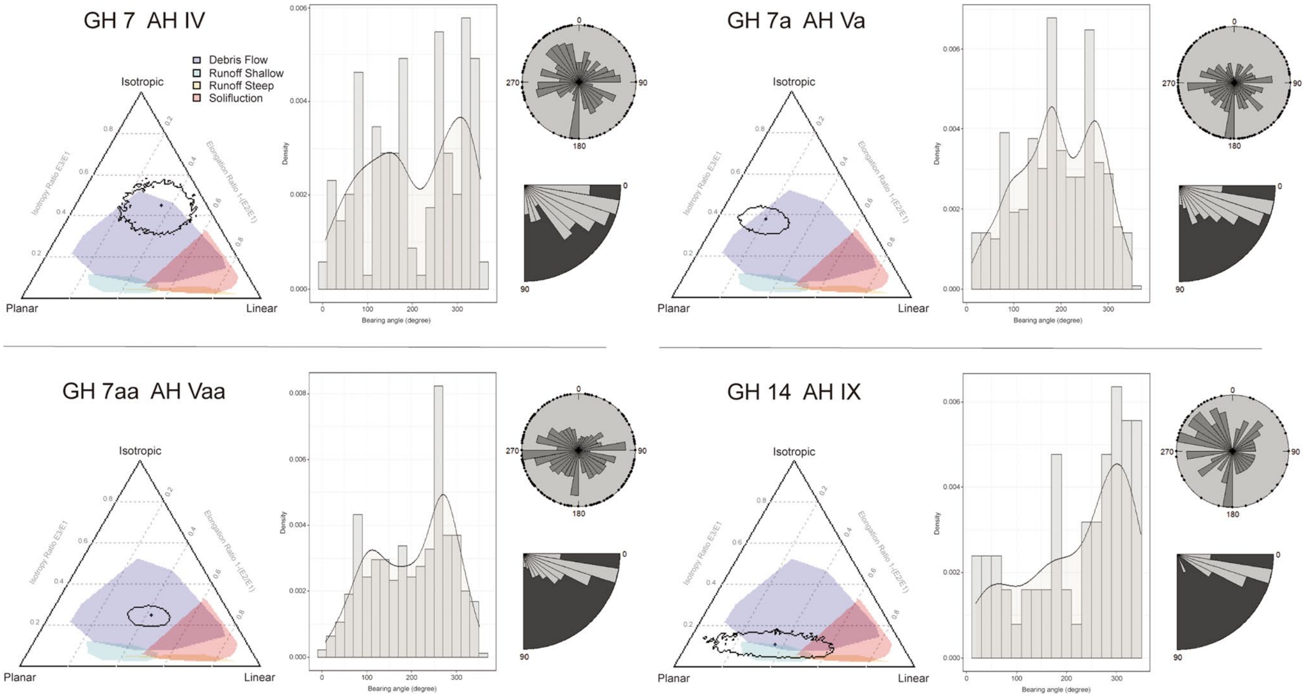
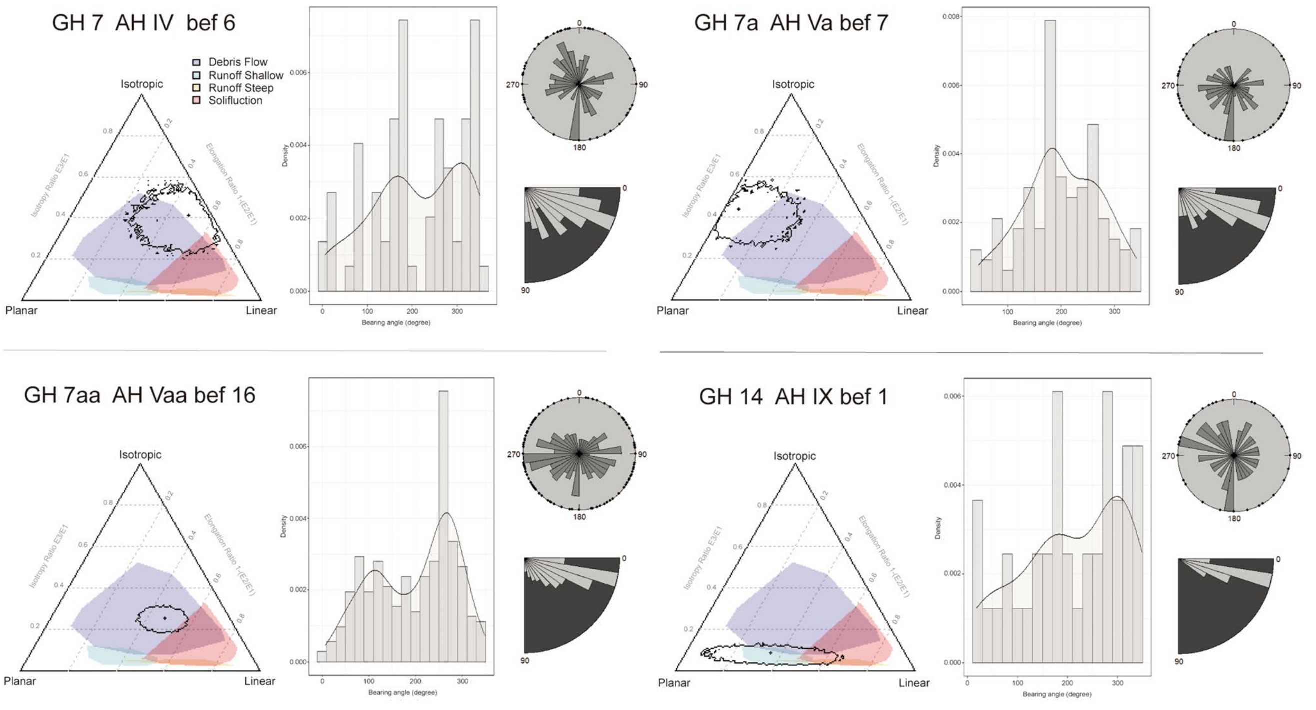


Fig. 9 Orientation analysis of the elongated archaeological material from the geological horizon 7, 7a, 7aa, and 14

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 µXRF 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


GH 7 AH IV bef 6

GH 7a AH Va bef 7

GH 7aa AH Vaa bef 16

GH 14 AH IX bef 1

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

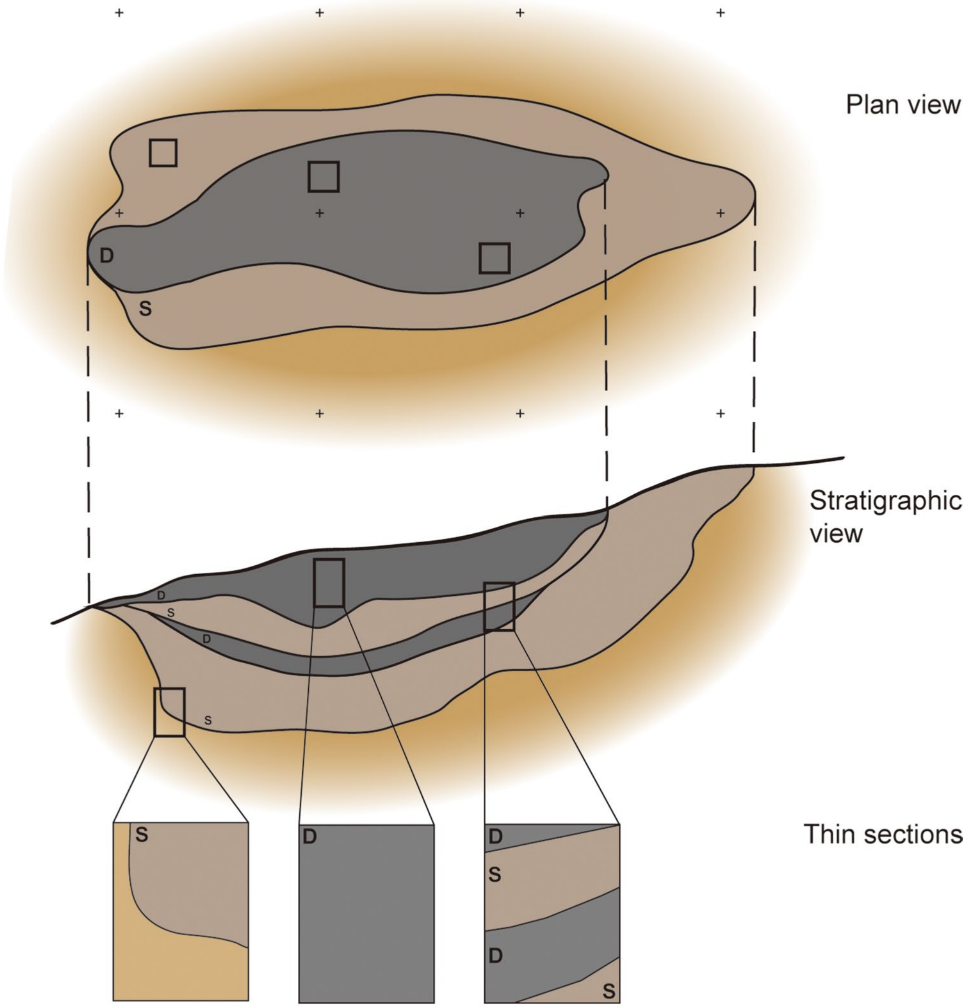


Fig. 11 Lateral and vertical variation model. The variation in microstratigraphic type within a single feature is likely impacted by the position of the samples. Thin sections preserving dumping (D) evidence come from the central area of the features and include the middle part of the feature section. 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 GH (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 GH 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 (~ 11°), which most resembles the slope inclination at Hohle Fels and a lower plunge variance (~ 9°). 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 Kulturpumpemodel (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; Marcazzan 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.

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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.

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

Declarations

Conflict of interest The authors declare no competing interests.

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Appendix III

Marcazzan D, Ligouis B, Mentzer SM, Miller CE. Experimental heated bones: organic petrology and Fourier Transform Infrared spectroscopy (FTIR) analysis on bones heated at low temperature in oxidizing atmosphere.

Experimental heated bones: organic petrology and Fourier Transform Infrared spectroscopy (FTIR) analysis on bones heated at low temperature in oxidizing atmosphere.

Diana Marcazzan [1], Bertrand Ligouis [1, 2], Susan M. Mentzer [1, 2], Christopher E. Miller [1, 2, 3]

[1] Institute for Archaeological Sciences, University of Tübingen, Hölderlinstr. 12, 72074 Tübingen, Germany
[2] Senckenberg Centre for Human Evolution and Palaeoenvironment, Tübingen, Germany
[3] SFF Centre for Early Sapiens Behaviour (SapienCE), University of Bergen, Post Box 7805, 5020 Bergen, Norway

Introduction

Bones are biological materials containing 70 wt% of inorganic material (White and Folkens 2005). A fresh bone consists of inorganic calcium phosphates precipitated in an organic collagen matrix (Currey 2002; Reidsma et al. 2016; Villagran et al. 2017). An idea of the proportion is: 20–30% collagen (protein), a triple helical structure formed by amino acid chains (polypeptides) (White and Folkens 2005); 60–70% calcium phosphates (bone mineral); and the remaining <10% comprises a combination of other components such as complex sugars, lipids, carbonates, Mg, Na, trace elements and metal ions (White and Hannus 1983; Posner et al. 1984; Pate and Hutton 1988; McCutcheon 1992; Currey 2002; Villagran et al. 2017). From the mineral point of view, the components (Villagran et al. 2017) are hydroxylapatite or hydroxyapatite (Ca5(PO4)3(OH)), bioapatite (a poorly crystalized calcium phosphate resembling hydroxylapatite), and carbonate hydroxylapatite (Ca5(PO4CO3)3(OH)) also known as dahllite.

In archaeology, bones (with horns, antlers, ivory and teeth) represent a significant part of the coarse fraction of a deposit (Schiegl et al. 2003; Dibble et al. 2009; Mentzer 2014; Villagran et al. 2017). Therefore, they are a central topic in many fields of research, such as palaeoanthropology, zooarchaeology, bone tool technology and even geoarchaeology. Bones rightfully enter the field of geoarchaeology when we found their fragments within a thin section (Villagran et al. 2017). For example, a bone fragment in thin section is recognizable by well-defined features, including a light-yellow colour in plane-polarized light (PPL) and a low-order white to grey autofluorescence (Villagran et al. 2017). A geoarchaeological analysis does not stop at the petrographic identification. In fact, a geoarchaeologist can apply a wide range of microanalysis to understand any alteration of the bone. By using different analytical techniques on bones, we can solve several archaeological issues, such as the one related to human behaviour, site formation processes, taphonomy and chemical diagenesis (Weiner et al. 1993, 2002; Schiegl et al. 2003; Porraz et al. 2015; Dal Sasso et al. 2016).

The investigation of heated bones is one of the main topics, as the behavioural implications of the burning of bones are many, especially in Palaeolithic contexts (Théry-Parisot 2002; Schiegl et al. 2003; Costamagno et al. 2005; Dibble et al. 2009; Mentzer 2014; Starkovich et al. 2020). Bones can burn for different processes and reasons (Clark and Ligouis 2010).

Bone fragments can burn incidentally when they are located underneath (Stiner et al. 1995; Bennett 1999; Pérez et al. 2017) a hearth (brush fires, burned due to proximity to combustion features). They can burn intentionally (Villagrain et al., 2017); because of cooking (Schiegl et al. 2003; Costamagno et al. 2005; Théry-Parisot et al. 2005); because of specific properties of the fire (Théry-Parisot 2002); and lastly because of site-maintenance practices (Clark and Ligouis 2010; Bosch et al. 2012; Starkovich et al. 2020). Ellingham et al. (2015) indicated the four phases a bone can undergo while burning. These phases are 1) dehydration; 2) decomposition; 3) inversion; 4) fusion.

With burning and along these phases, the structural and chemical characteristics of bones change (Etok et al. 2007). Macroscopically and microscopically, we can identify these changes, such as colour change (Stiner et al. 1995; Hanson and Cain 2007; Villagran et al. 2017), fracture patterns and mechanical strength (Thompson et al. 2009), and crystallinity (Ellingham et al. 2015). Among the most common techniques to address these manifestations, we can use organic petrology (Clark and Ligouis 2010), Fourier-transform infrared spectroscopy (FTIR) (Lebon et al. 2008, 2010; Thompson et al. 2009, 2013), x-ray fluorescence (XRF) (Kalsbeek and Richter 2006; Thompson et al. 2011), x-ray diffraction (XRD) (Rogers and Daniels 2002; Piga et al. 2008), and many others (detailed overview in Lambrecht and Mallol 2020).

Within the FTIR analysis, the first step has been (Thompson et al. 2009; Ellingham et al. 2015; van Hoesel et al. 2019) the investigation of changes in the spectra collected from bones experimentally burned. The peaks change and modify when increasing the temperature of burning (for a complete overview van Hoesel et al. 2019). In particular, Thompson and colleagues (2009; 2011) saw that measuring certain areas of the spectra could identify useful indices for studying the degree of bone burning. The first works mainly relied on the Crystallinity Index (CI). The CI also called the ‘splitting factor’ measures the order of the crystal structure and composition within the bone (Surovell and Stiner 2001; Thompson et al. 2009). It is a function of the extent of splitting of the two absorption bands at 605 and 565 cm-1 (Olsen et al. 2008).

However, these works showed how temperature, duration of burning and other variables (Thompson et al. 2011) can influence the CI value. Further, problems arise when the goal of the analyses is to identify low degrees of temperature. The bones mineral mainly change around temperatures of 600 °C, i. e. when the organic part of the bone burn (van Hoesel et al. 2019). Van Hoesel and colleagues also point out that only minor changes are visible with the FTIR at low temperatures.

Regarding the organic petrology, this technique is still not used extensively for the study of burnt bones and few studies have been carried out. However, the first results in its application to archaeological bones showed that fluorescence colour undergoes changes upon burning (Clark and Ligouis 2010) and that autofluorescence decreases (Schiegl et al. 2003). Recently, Lambrecht and Mallol (2020) used fluorescence spectroscopy to study the autofluorescence of cow bones that had been heated experimentally. This study also showed that a colour shift in fluorescence occurs before combustion or charring, which lasts until calcination (Lambrecht and Mallol 2020). Further, they highlighted the potential of fluorescence studies for low temperatures (100-300°C) along with archaeological assemblages.

In this study, we apply Fourier-Transform Infrared spectroscopy (FTIR) (Berna 2017) and organic petrology (Ligouis 2017) to our samples. The sample includes lamb, roe deer, and horse bone fragments, heated every 50 °C in oxidizing conditions. The maximum temperature tested is 500 °C. With the application of FTIR, we want to test whether we can build a temperature prediction model by increasing the sample variability and by trying to use other types of measurements, such as the whole spectrum. By studying the entire spectrum of bones combusted at low temperatures, we aim to investigate the extent to which collagen (absorption bands from 1151 to 1700 cm-1) aids and contributes to identifying combustion temperatures. Finally, previous studies have mainly focused on KBr (potassium bromide) pellets and ATR methods. In our analysis, we decided to collect data with micro-FTIR to increase the coverage of FTIR analysis. At the same time, using polished sections, we tried to verify the applicability of FTIR analysis in a possible thin section study.

Through the employment of organic petrology, we seek to expand our knowledge of the changes occurring at low temperatures. As mentioned, many techniques, including FTIR, have problems identifying changes at low temperatures (van Hoesel et al. 2019; Lambrecht and Mallol 2020) that could be useful to predict the degrees of combustion heat. We decided to use organic petrology because, given previous studies on fluorescence in controlled contexts (Lambrecht and Mallol 2020) and on archaeological material (Clark and Ligouis 2010), this technique seems promising, especially for the range of temperatures focus of our experimentation.

Fig. 1: Burnt bones analysed in this experiemtnal work. 1) Lamb; 2) Roe

Sample preparation

In order to perform the burning experimentation, we used four sets of osteological samples: modern lamb femur (LA), modern roe deer metacarpus (RO), and modern horse rib (HO) and radio-ulna (HOU) (Fig. 5). LA, RO, And HO were macerated in water at a constant temperature (30 °C), while HOU were air-dried over a few months. After cutting the bones and removing the periosteum and marrow from HOU, we burnt them at low temperatures from 20°C to 500°C, at 50°C intervals in an oven with oxidizing conditions (Carbolite Gero 30-3000 °C). The heating rate increased by 10 degrees per minute. Due to fat burning, the temperatures went ca 10 °C above the desired setpoint and then down to the desired temperature in a few seconds. After reaching temperature, we let the bones burn for 45-50 minutes (Thompson et al. 2009). We then left them to cool for 24 h outside the oven. Because of different fat content, we burnt the HOU separately from the others.

After the burning, we cut the samples using an Isomet precision sectioning saw to avoid damage to the bone structures, and then we dried them in a desiccator for several hours. Half of each bone has then embedded in low viscosity Araldit under vacuum. The polished sections were prepared for microscopic analyses according to the procedures used in organic petrology (Taylor et al. 1998). However, we dry polished the thin sections under very low pressure using a sequence of grinding and polishing steps followed by a final polishing step using aluminium oxide powder. For the other half, we immersed the bone samples in a 1:2 chloroform/methanol solution under agitation overnight to remove the lipid components. We repeated the operation until the yellowish colour disappeared. They were rinsed with acetone and then with millipolar water before being allowed to dry at room temperature. After the lipid extraction, we grounded the bones with Mini Mill (pulverisiette23) using three stainless steel balls (5mm diameter).

Methods

Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) consists of the identification of the functional mineral groups in a powdered sediment sample, in sediment mounted on a thin section, or in resin-impregnated sediment blocks (Berna 2017). FTIR is a quantitative analysis useful for determining the mineralogical composition of sediments and archaeological materials (Weiner et al. 2007), to understand their diagenesis and alteration (Berna 2017). This technique has become particularly important in the study of burned materials (Mentzer 2014), through the identification of changes in the crystal structure of clay minerals, carbonates, phosphates, and sulphates caused by heat. FTIR may also be paired with an optical microscope for the direct identification of minerals ion the thin sections themselves (Berna 2017).

For this study, I employ micro-FTIR and ATR (attenuated total reflection) using FTIR bench (Cary 660, Agilent) attached to a microscope with integrated ATR on polished impregnated polished blocks and powdered bone samples. Measurements were performed in total reflectance between 4000 and 400 cm-1 wavelengths at 4 cm-1 resolution.

Spectra analysis and statistical models

The collection of spectra and the calculation of specific indices have been used in many studies to facilitate the application of multivariate analyses for a quantitative investigation of burnt bones (Thompson et al. 2013). Thompson and colleagues (2013) tested the validity of 5 new spectral indices of heat-induced crystallinity change by using a statistical classification model to predict the burning temperature of a validation set. They applied at first a Principal Component Analysis (PCA) to understand the strength of relationships within complex series of data (Thompson et al. 2013). After that, they performed a Linear Discriminant Analysis (LDA) which allowed them to build a statistical classification starting from a training dataset and classify temperatures without the user input.

In our study, we first performed a PCA to check the data and identify any outliers. Secondly, we applied a Partial Least-Square (PLS) regression analysis. PLS build predictive models based on local least-squares fits (Andrade-Garda et al. 2009) when the factors are many and highly collinear (Tobias 1995), like the spectral variables. It is usually used in chemistry to predict a certain property of the sample. Therefore, for our analysis, we used PLS analysis on the whole spectrum of a training set to predict the combustion temperature in a validation set. The training set includes spectra from HO and HOU, and the validation set has the spectra from LA and RO. We performed the analysis on both powdered and polished samples. To accomplish the statistical analysis, we used JMP® 16.0.0 statistical software (license provided by the University of Tübingen, Germany). All ATR-FTIR and micro-FTIR spectra were pre-treated (Essential FTIR and Resolution Pro), baseline corrected, CO2 zapped, and normalized (standard normal variate normalization SNV) before application of multivariate analysis.

Organic petrology

Organic petrology is well established to assess the reflectance of plant tissues to measure the degree of maturation of organic matter in peat, brown coals, carbons and sedimentary rocks (Borrego et al. 2006). In this paper, we measured the bone reflectance under oil immersion at a magnification of 500x and a wavelength of 546 nm (monochromatic light), using a measuring diaphragm of 2 µm diameter. On the charred bones, we calibrated the photometer with two standards materials of known reflectance covering the interval of measures: 0.589% (saphir, 546 nm, 23°C), 3.112% (cubic zirkonia, 546 nm, 23°C). We performed at least 100 measurements when the size of the bone sample allowed it. Depending on the type of bone, the measurements are spaced 10 to 40 µm apart along a transect from one edge of the disc to the other. Lastly, we examined the fluorescence to characterize the fluorescence properties of the bones through the temperature range of the heat experiment. The variations of the colours and the intensity of fluorescence will be particularly taken into account and interpreted as the result of the alteration due to burning.

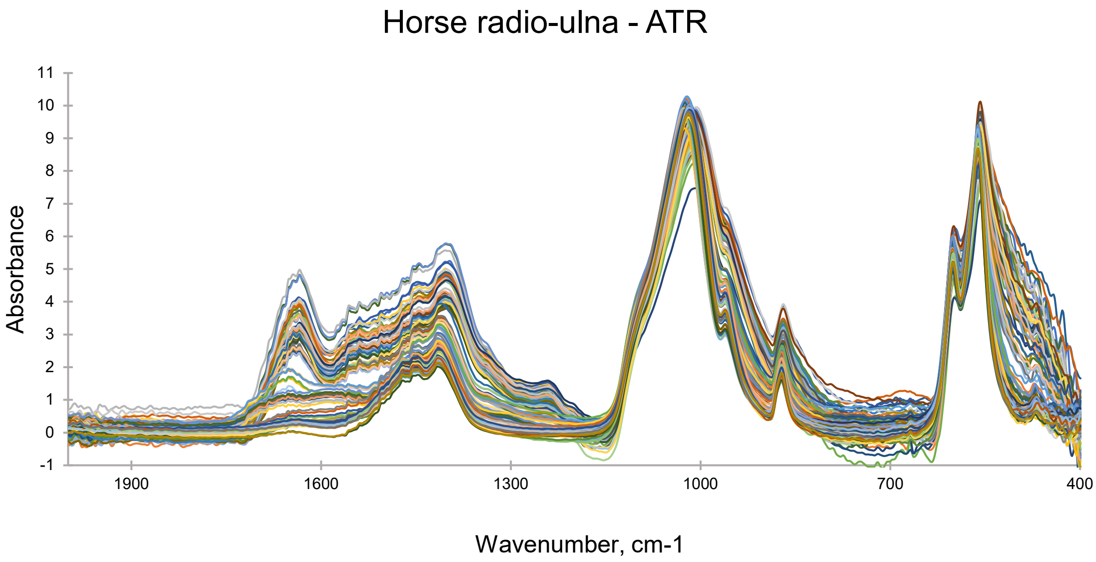

Fig. 2: Example of FTIR-ATR spectra of the powdered bones (HOU).

Results

FTIR analysis and quantification using multivariate regression

In accordance with observations done in previous studies (Thompson et al. 2013), the spectra for the heated bones display changes due to temperatures (Fig. 2). At low

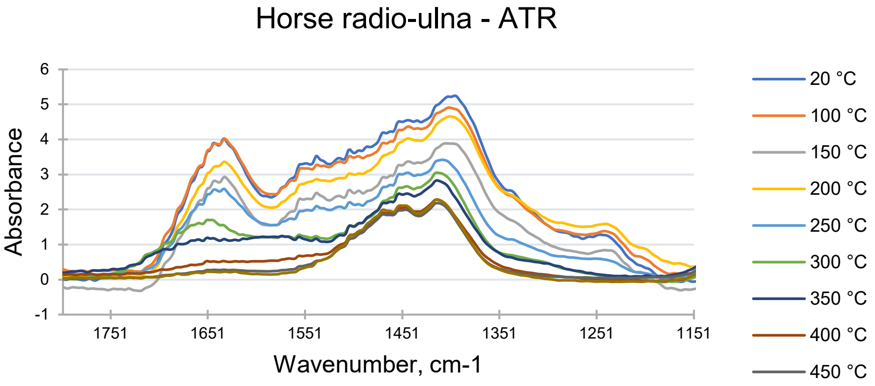

Fig. 3: Detail of spectra at different degrees. Note the area between 1151 and 1700 cm-1 diagnostic of the collagen content. With the increase of the temperature the collagen peaks decrease.

temperatures this changes are visible especially in the collagen area (Fig. 3) from 1151 to 1700 cm-1, where with the increase of the temperature we have the most variation in the peaks.

The first PLS models that we built on individual peak areas and peak measurements had very low initial r-squared values. Thus, as little change is visible in the rest of the spectra at low temperatures, we decided to use PLS on the entire spectra (from 399 to 2000 cm-1). Secondly, we built the model on the spectra without the collagen area (from 399 to 1151 cm-1). The decision to check the model even without collagen stems from the fact that collagen may not be preserved in an archaeological deposit (Bouchard et al. 2019).

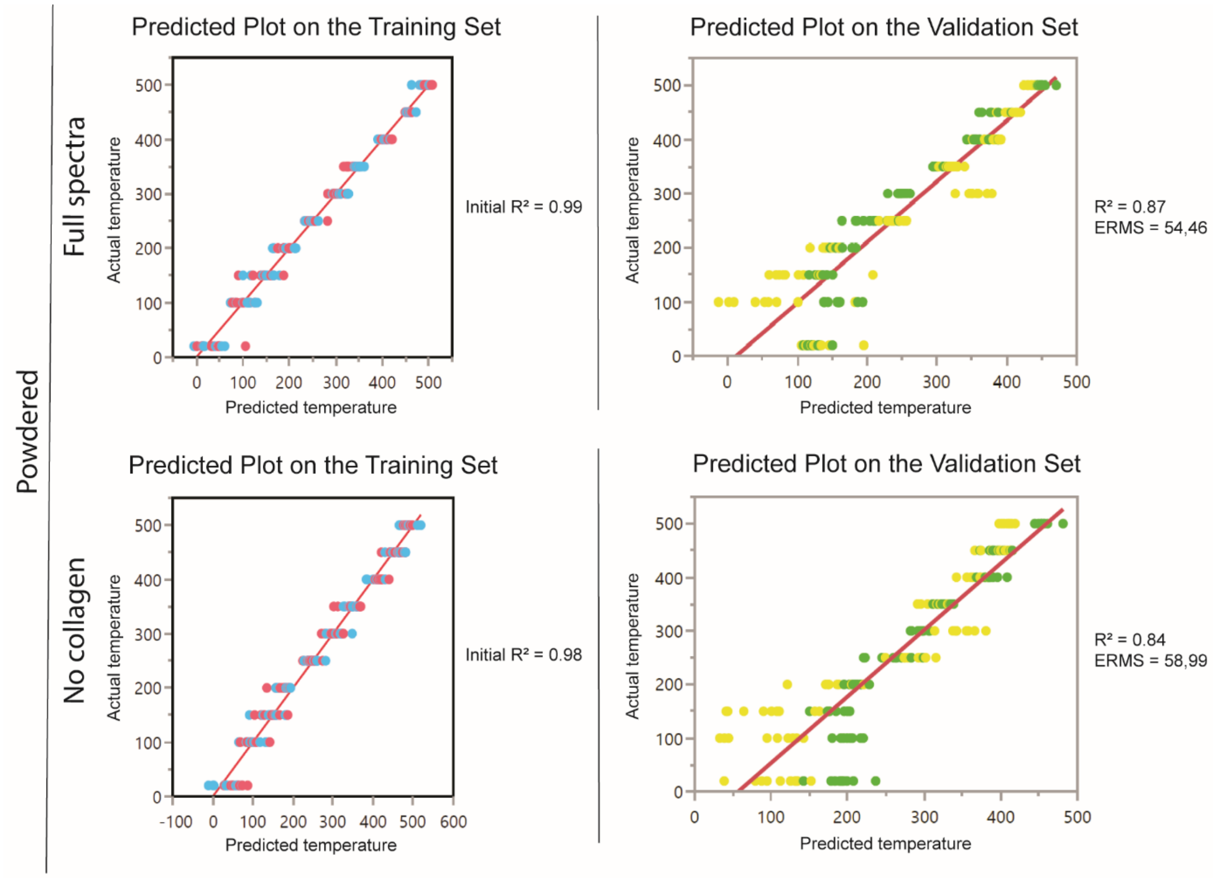

Fig. 3: PLS diagnostic Plots for the powdered bones. There are the diagnostic plots from the PLS analysis on the full spectra and on the spectra without the collagen area. On the left note the predicted plots on the training set (HO in red and HOU in blue), and on the right the model fit on the validation set (LA in yellow and RO in green).

The results on the full-spectra provided, for the powdered training set, an initial r-squared value of 0.99. We had a similar initial r-squared value (0.99) for the polished training set. From the graphs (Fig. 3 and 4) one can see that, especially for powdered bones, the model works better for a range of temperatures between 300 °C and 450 °C. However, the graphs show that the predictive formula for temperatures (Fig. 3 and 4), given by both training sets, does not have a good fit for the validation sets. By checking the R-squared, the validation set on powdered bones gives 0.87, while the validation set on polished bones presents a value of 0.88. The Root Mean Square Error (RMSE) is a bit lower for the powdered bones (54,46) (Fig. 3), but not acceptable to say that the model work. A similar outcome came from the models built with the spectra without the collagen area. The powdered training set provided an initial r-squared value of 0.98, while the polished bones gave a 0.96 value. Even in this case (Fig. 3 and 4), the graphs that the predictive formula for temperatures (Fig. 3 and 4) given by both training sets does not have a good fit for the validation sets. By checking the R-squared, the validation set on powdered bones gives 0.84, while the validation set on polished bones presents a value of 0.82. The RMSE is a bit lower for the powdered bones (58,99), but not acceptable to say that the model works.

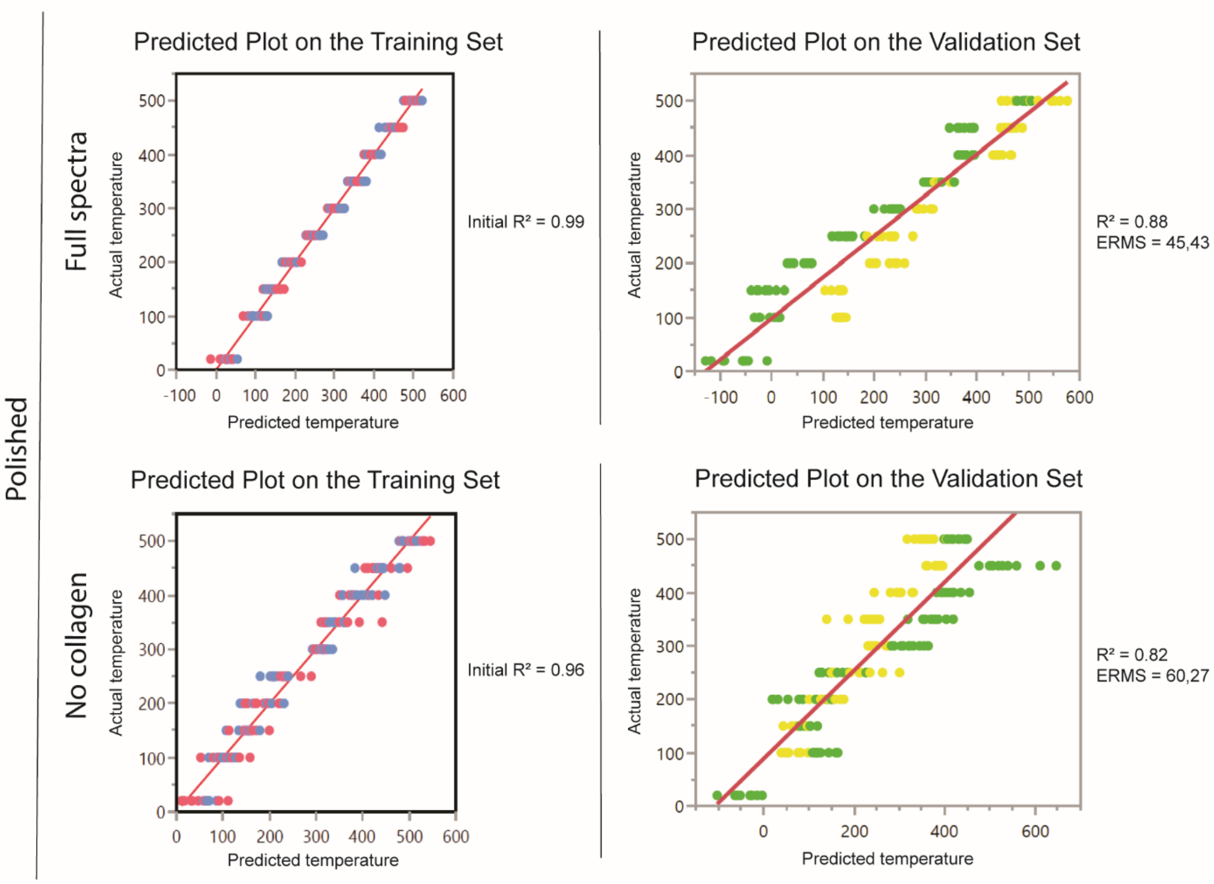

Fig. 4: PLS diagnostic Plots for the polished bones. There are the diagnostic plots from the PLS analysis on the full spectra and on the spectra without the collagen area. On the left note the predicted plots on the training set (HO in red and HOU in blue), and on the right the model fit on the validation set (LA in yellow and RO in green).

Organic petrology

After the organic petrology analysis, we divided the bones into 4 categories due to the characteristics (full description in supplementary information) that certain degrees share. For this reason, I will present the results in the following categories: 20°C, 100-150°C, 200-300°C, and 350-500°C. At their initial state, 20°C, the colour of the bones in polished sections varies from whitish (lamb - LA) to light grey (roe deer - RO) to light grey/brown (horse rib - HO) to light orange-brown (horse ulna - HOU). In reflected white light under oil immersion, the surface of bones appears blurry and bright (Fig 6-7-8-9). HO and HOU show heterogeneity while LA and RO have more homogeneous colours. These optical properties reflect very low values of the reflectivity of bones. The reflectance of bones varies from 0.03%R to 0.09%R (Fig. 5). In fluorescence mode the surface of the bones appears blurry and bright (Fig 6-7-8-9). The fluorescence colour is mainly pale green of low to very low intensity (Fig 6-7-8-9).

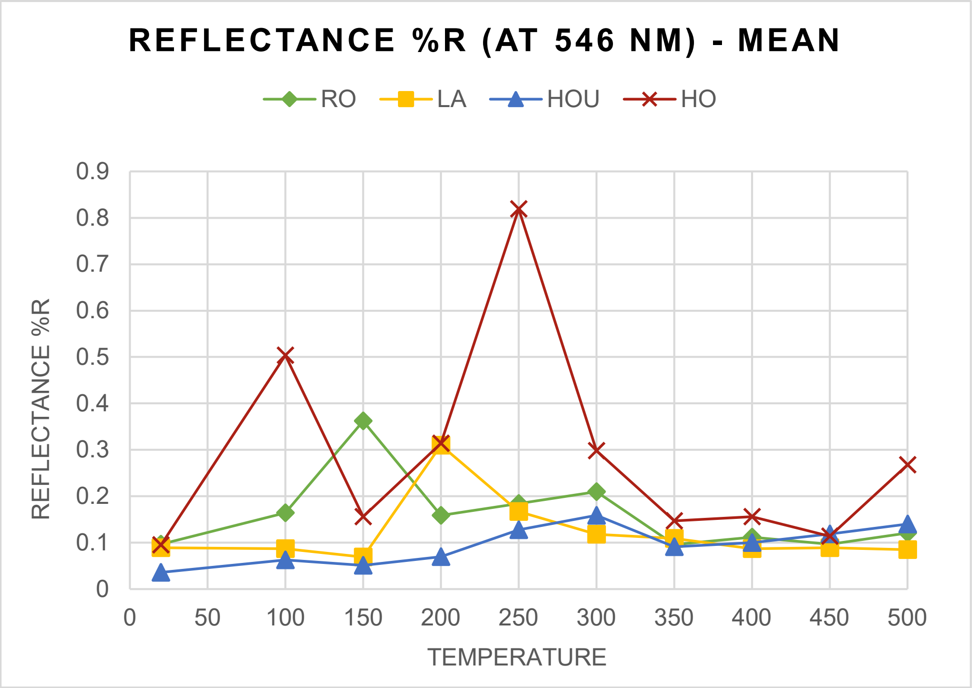

Fig. 5: Mean values of reflectance %R (at 546 nm).

Bones between 100 and 150°C have little change of colour, which takes on a more intense brown shade. In reflected white light under oil immersion, the surface of bones still appears blurry but with variable brightness (Fig 6-7-8-9). The most significant changes are at the edges of the bones, whose colour becomes greyish (Fig 6-7-8-9). Locally, the edges have also a cracked appearance. The interior of the bones has optical properties similar to those observed in the initial state. However, some areas become noticeably darker others brighter (bright spots). There is a slight increase in reflectance values in most bones. Small increases in reflectance were recorded in HOU (up to 0.06%R), HO (up to 0.5%R) and RO (up to 0.3%R) bone, while the reflectance of the LA remains unchanged (Fig. 10). The fluorescence properties remain unchanged for LA, which is consistent with its characteristics in reflected white light. As regards HOU, HO and RO, the initially predominantly green fluorescence tints shift significantly towards yellow or even orange (towards longer wavelengths) (Fig 6-7-8-9).

Above 200°C (range 200-300°C), the four types of bone behave slightly differently due to their intrinsic nature. A common point is the existence of a reflectance peak which appears more or less early, that is to say at a more or less high temperature. Beyond this peak, the reflectance values decrease to stabilize and form a plateau. From a macroscopic point of view, the colour of the bones changes significantly. They all take on a more or less reddish-brown colour that turns black at 300°C. In reflected white light under oil immersion, the surface of bones appears blurry with very variable brightness (Fig 6-7-8-9). There are consequent changes at the edges of the bones, where colour becomes dark grey, grey-brown, and orange-brown (Fig 6-7-8-9). Locally, the edges have also a fissured, finely granular and porous appearance. The interior of the bones has very heterogeneous optical properties. Here the bone structure is visible. Dark areas cohabit with lighter or very bright areas. The reflectance values are heterogeneous in most of the bones (Fig 6-7-8-9). For each type of bone, this temperature range has the highest values of reflectance and the presence of a peak (Fig. 10). The fluorescence colours (green, yellow, orange) and the fluorescence intensity show great variability from one domain to another (Fig 6-7-8-9). This observation agrees with the heterogeneity of the properties of bones in reflected white light. The bones subjected to a temperature of 300° C possess domains with very low fluorescence and even domains having lost fluorescence (Fig 6-7-8-9). A remarkable fact is that at 300 °C, in HOU, appears fine char coatings in some Haversian canals and along the bone edge.

The last interval ranges between 350 and 500°C. Macroscopically, the black colour that bones take on around 300/350°C also characterizes the bones up to 400°C or even beyond. From 450 to 500°C, grey shades or even rather dark brown or reddish-brown colours (LA and RO) replace this black colour. In white reflected light, the optical properties acquired in the temperature range 200-300°C remain unchanged. The surface of bones appears still blurry with a very variable brightness (Fig 6-7-8-9). Transformations at the edge of the bones intensify with increasing degree of fissuring even inside the bones, where many areas also become finely granular. The edges of the bones becomes dark grey, light grey, grey-brown, orange-brown (Fig 6-7-8-9). The interior of the bones has very heterogeneous optical properties. The predominant colours including grey-brown, orange-brown, yellow-brown, orange and dark grey-brown. These colours have numerous internal reddish and yellow reflections often observed in archaeological bones (Fig 6-7-8-9). From 350°C, the reflectance values decrease for all the bones to stabilize at values around 0.10%R and 0.08%R for the LA (Fig. 10). A slight increase in reflectance is recorded at 500°C except for LA whose reflectance values remain stable around 0.08%R (Fig. 10). Observations in fluorescence mode show a general decrease in fluorescence intensity of the bones (Fig 6-7-8-9). The fluorescence colours are mainly pale or dark: pale green, pale yellow-green, dark green, dark brown (Fig 6-7-8-9). The temperature range 350-450°C see the formation of thin char coatings. It is found along the edges of bones and in some haversian canals. However, at 500°C char is absent or rare in most of the bones.

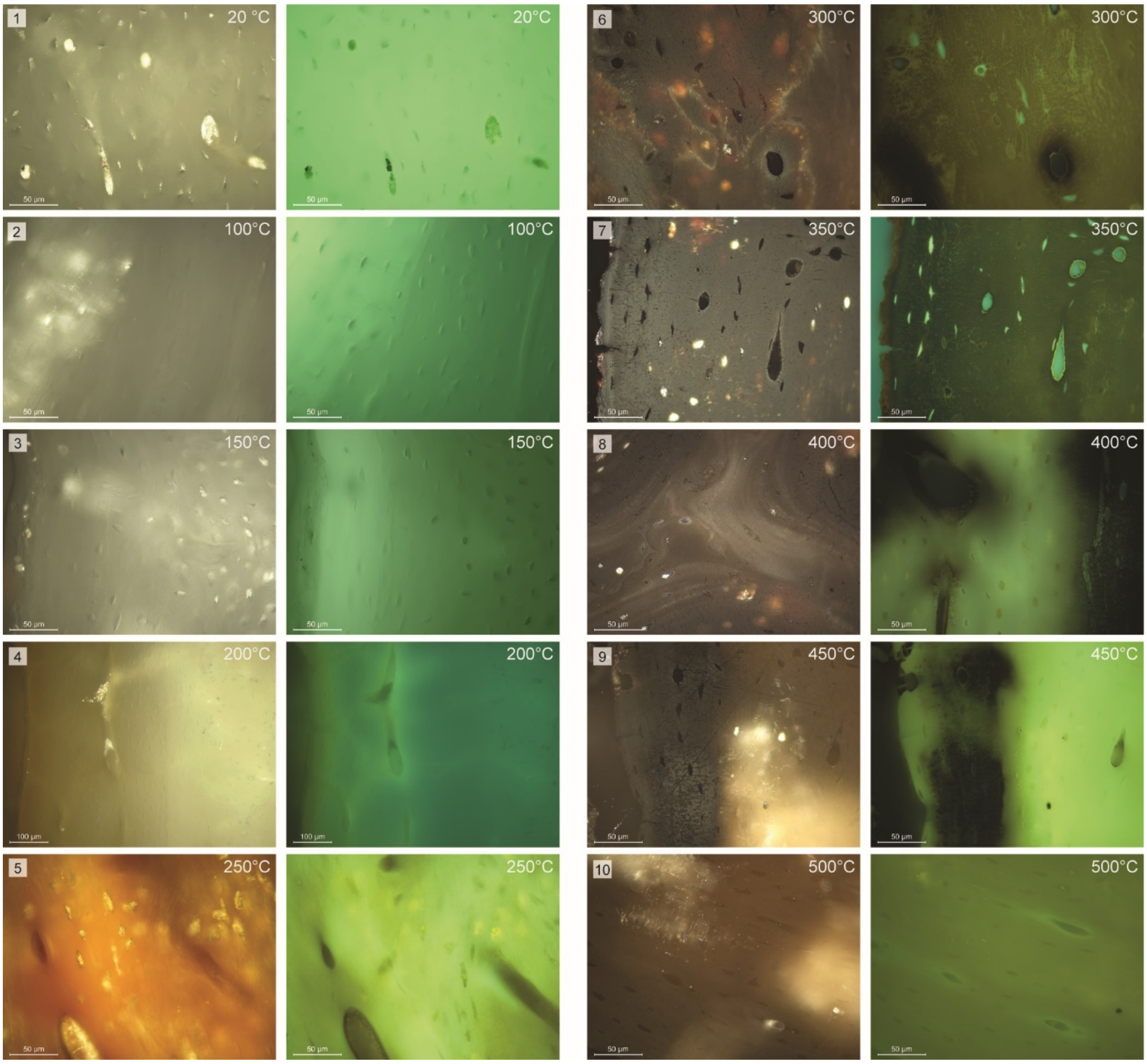

Fig. 6: Microphotographs of lamb femur in reflected light and fluorescence mode for each burning temperature.

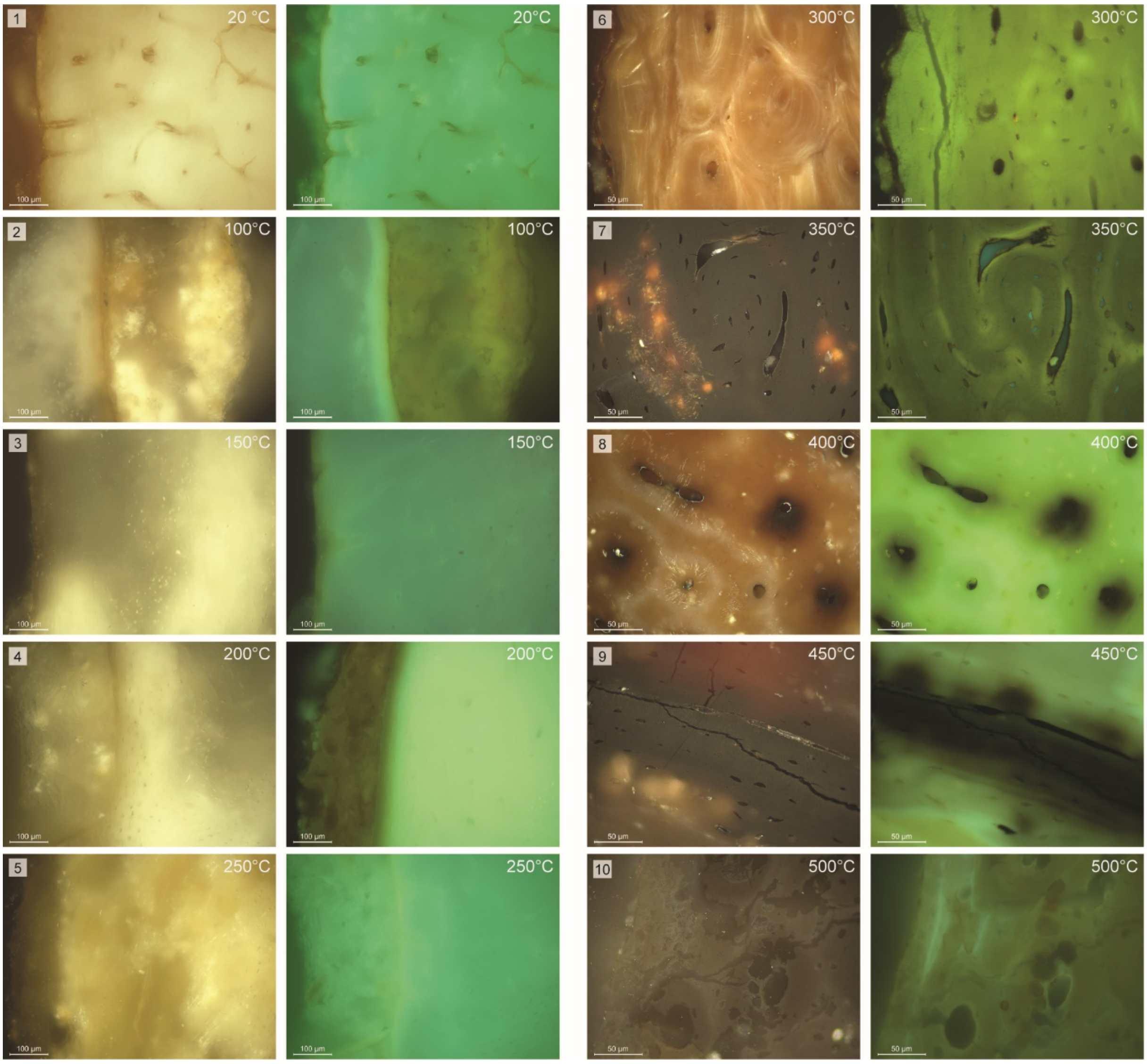

Fig. 7: Microphotographs of roe deer metacarpus in reflected light and fluorescence mode for each burning temperature.

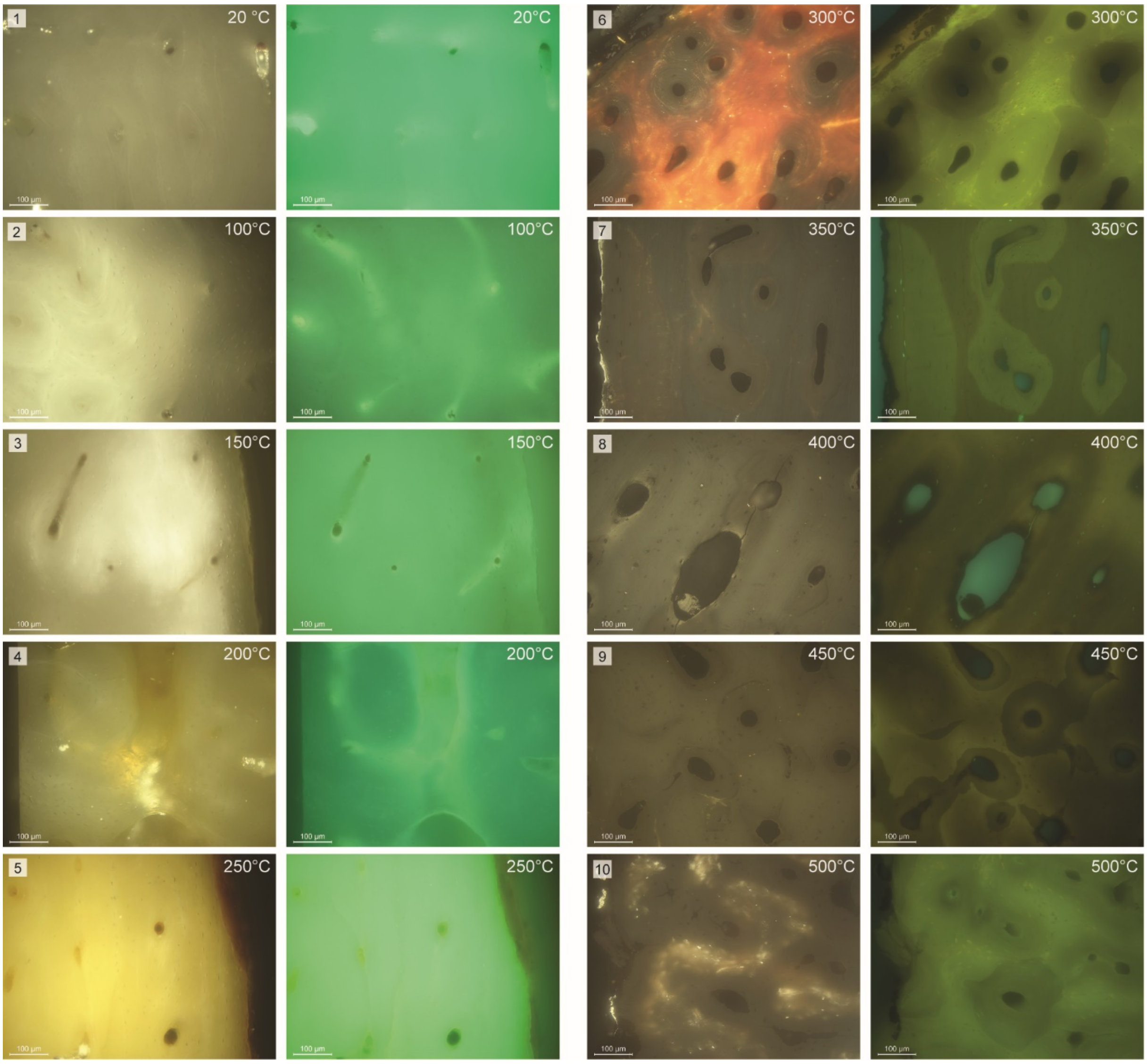

Fig. 8: Microphotographs of horse rib in reflected light and fluorescence mode for each burning temperature.

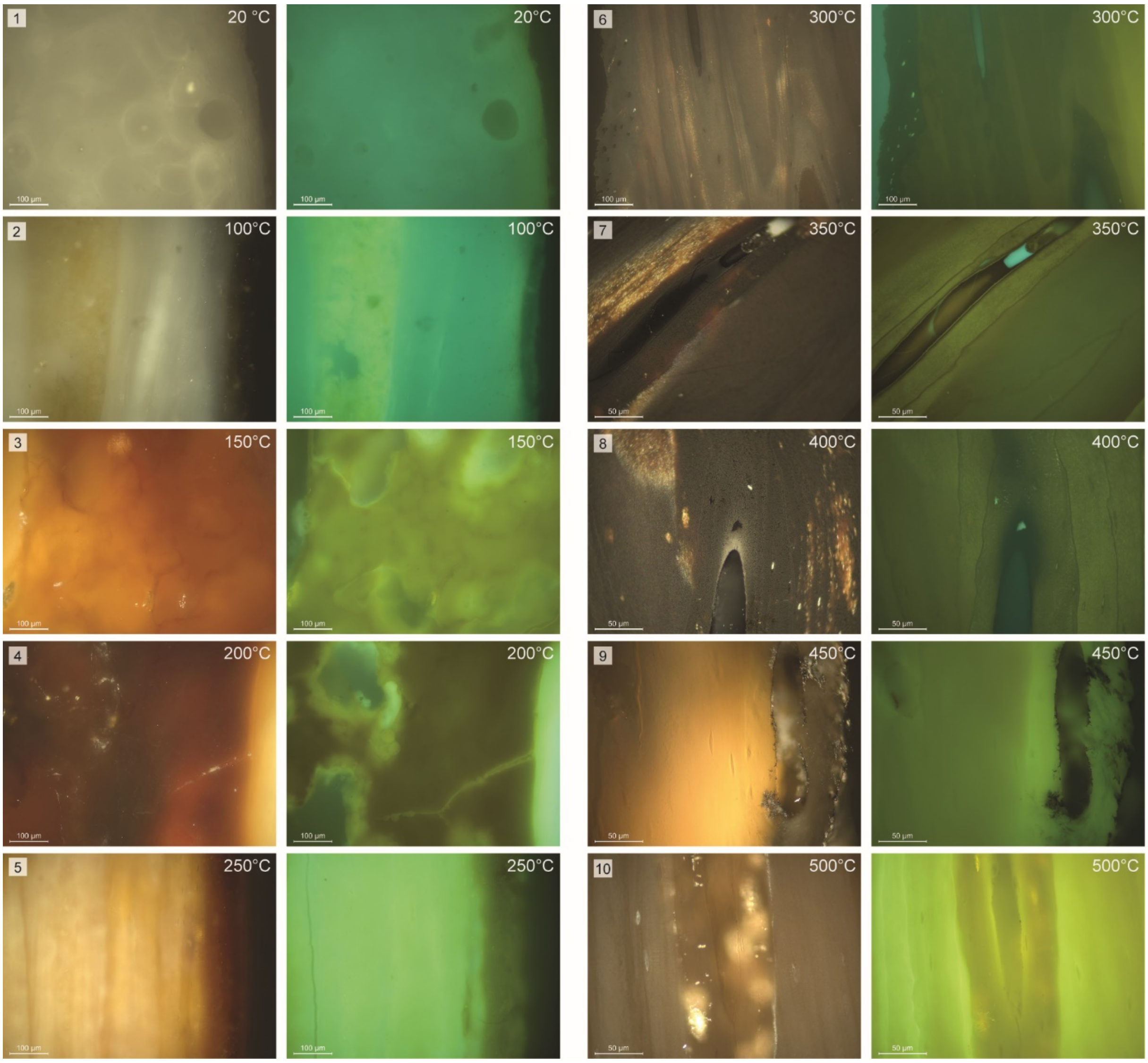

Fig. 9: Microphotographs of horse radio-ulna in reflected light and fluorescence mode for each burning temperature.

Discussion and conclusion

To better understand hominin behaviour and the beginning of fire use and control, it is fundamental to increase our knowledge of the heated bones (van Hoesel et al. 2019; Lambrecht and Mallol 2020). Heated bones are an integral part of the material remains of an archaeological deposit (Villagran et al. 2017; van Hoesel et al. 2019). Their discovery, especially in large quantities, as at Hohle Fels (Schiegl et al. 2003; Marcazzan et al. 2022), may reflect the choices of the fuel type used for domestic hearths (Théry-Parisot 2002; Costamagno et al. 2005; Théry-Parisot et al. 2005). Indeed, bones can be used as the main part of the fuel, promoting the production of a high flame and also a rapid extinguishing of embers (Théry-Parisot 2002). Moreover, if used together with decomposed wood, bones can facilitate fuel supply. Indeed, bones are a common waste product at Palaeolithic sites and decomposed wood is more readily available than fresh wood, the use of which also imposes certain restrictions (Théry-Parisot 2001).

Our experimentation on heated bones fits into an already extensive bibliography (Lebon et al. 2008; Thompson et al. 2009; Clark and Ligouis 2010; Lebon et al. 2010; Thompson et al. 2011, 2013; van Hoesel et al. 2019; Lambrecht and Mallol 2020). We decided to focus on low temperatures (up to 500 °C) because, in Palaeolithic contexts, it is more common to identify bones around these burning degrees (Schiegl et al. 2003; Marcazzan et al. 2022) and because of the known problems that occur using FTIR in this temperature range (van Hoesel et al. 2019; Lambrecht and Mallol 2020). Furthermore, previous FTIR analyses had already highlighted the need for standardised experimental parameters, such as the sampling of "the periosteal surface at the mid-point of the diaphysis of a long bone, preferably the femur" (Thompson et al. 2011:173), in order to replicate and build good predictive models (Thompson et al. 2011; 2013). The main problem with standardised parameters is their application to archaeological research. Within an archaeological assemblage, there are many variables, and it is impossible to find the same parameters as in a controlled experiment.

By increasing the variability in our samples, the PLS analysis showed good results for the training sets, with an initial r-squared value of around 0.98 for the powdered bones and 0.99 for the polished bones (Fig 3 and 4). However, we were not able to reach with the spectra analysis and peak measurements a correct classification rate able to predict the burning temperature for the validation set. Similar results we have by taking the collagen area out the PLS model.

Instead, organic petrology proved to be a valid technique to study combusted bones at low temperatures. Observations made on fluorescence are in line with recent studies (Lambrecht and Mallol 2020). Furthermore, the data on the fluorescence and other characteristics, such as the reflectance values, allowed us to create four main ranges of temperatures: 20 °C, 100-150 °C, 200-300 °C, and 350-500 °C. On an important note, with organic petrology, we were able to detect the appearance of fat-derived char in the temperature range 350-450 °C. However, the char residues in most of the bones were absent or rare at 500 °C. This information is particularly useful when in thin section, from combustion features in-situ, we identify char in strict correlation with burnt bones. The copresence of char and bones may suggest that the burning temperatures were around

300-400 °C and only in rare cases over 500 °C, which is a range usually related to a campfire.

Our experimental work shows that solely FTIR analysis cannot be the only technique used to identify burnt bones. In particular, FTIR is not reliable when more variables arise. This is a problem for its application to archaeological material or thin section analysis. For example, in thin section, no data on the species or the type of combustion are available, and the ideal situation of standardising parameters is not possible. Certainly, FTIR is a useful tool to trace changes, and it works especially well in a frame of low-medium-high temperatures. However, at low-medium temperatures, it must be used carefully and with the support of other techniques such as organic petrology. With a view to future perspectives, this work should be concluded with experimentation in a reducing condition or implementing the organic petrology analysis by adding higher temperatures. Under different conditions of atmosphere (Reidsma et al. 2016; van Hoesel et al. 2019), changes in the bones may differ.

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Supplementary information

Table 1. Organic petrology observation for the lamb bones. The ID is formed by LA, which stands for the species, and a number, which stands for the temperature degrees.

ID	Colour	REFLACTANCE%R (at 546 nm)					OPTICAL PROPERTIES		Fat-derived char
		Interval	Mean	measurements	Standard deviation	Histogram characteristics	Reflected white light	Fluorescence mode	
LA20	Whitish	10 µm	0.089	87	0.055	Unimodal with rare outliers	Blurry and bright surface, yellowish-grey	Blurry and bright surface Colours: very pale green, very low intensity	-
LA100	Whitish	10 µm	0.087	100	0.043	Unimodal with a right skewed distribution	Blurry surface with variable brightness, light grey to dull grey	Blurry surface Colours: very pale green, low intensity	-
LA150	Whitish	10 µm	0.069	100	0.041	Unimodal with a right skewed distribution	Blurry and bright surface, light grey to middle grey. Dull grey-brown near the edge of the bone	Blurry surface Colours: very pale green very low intensity	-
LA200	Light brown to orange	10 µm	0.310	100	0.463	Unimodal with a skewed distribution (right) and few outliers	Blurry surface, light grey-brown, grey-brown, brown, dark grey. Few very bright domains (high reflecting) showing whitish-yellow color	Blurry surface Colours: very pale green, yellow-green, low to very low intensity	-
LA250	Light brown Dark brown, black	30-40 µm	0.167	100	0.173	Slightly bimodal with a skewed distribution (right) and few outliers	Blurry surface, dark grey (edge), grey-brown, orange-brown, light brown, brown. Some yellowish-brown domains show high brightness. Other greyish-yellowish domains are fibrous with high reflecting micrograins	Blurry surface Colours: pale green, brown-green, bright yellow-green, middle brown, orange-brown, very low to medium intensity	-

						The edge of the bone are partly granular and few fine cracks are visible		
LA300	Black	40 µm	0.118	64	0.023	Narrow and unimodal	Middle grey to dark grey with numerous reddish internal reflections. Numerous fine cracks and pores affect the entire bone. Some domains are fine granular	Colours: pale green-yellow, yellow-brown, dark brown, orange-brown, very low to low intensity Some domains are non-fluorescing	-
LA350	Black	10 µm	0.109	100	0.017	Narrow and unimodal	Middle grey to dark grey with reddish internal reflections. Numerous fine cracks mostly perpendicular to the edge line affect the entire bone	Colours: pale green, brown, dark brown, orange-brown (near the edge), low to medium intensity Near the edge of the bone the fluorescence can be very heterogeneous and some domains are non-fluorescing	-
LA400	Black	10 µm	0.087	100	0.035	Unimodal with two outliers showing local variability in reflectance	Near the edge, middle grey to dark grey, whitish granular in some domains and presence of numerous fine cracks mostly perpendicular to the edge line The middle part of the bone is middle grey, dark grey, grey-brown, whitish granular. This part shows	Colours: pale green to pale yellow-green, low to medium intensity Near the edge of the bone the fluorescence can be very heterogeneous, pale green, yellow, dark brown and some	char coating in the haversian canals along the bone edge

							rare domains of slightly higher reflectance	domains are non-fluorescing	
LA450	Dark-brown to reddish brown Black at the periphery	10 µm	0.089	88	0.096	Unimodal with few outliers showing local variability in reflectance	Near the edge, light grey to dark grey and presence of numerous fine cracks mostly perpendicular to the border line. The middle part of the bone is generally bright grey-orange or bright brown-orange. This part may have strong reflecting yellowish spots and lenses	Colours: pale green to pale yellow-green, low to medium intensity Near the edge of the bone the fluorescence can be very heterogeneous, pale green to dark brown	/
LA500	Dark-brown to reddish brown	10 µm	0.085	100	0.013	Narrow and unimodal	Blurry surface, grey, grey-brown, orange-brown. Numerous fine cracks mostly perpendicular to the edge line affect the entire bone. Yellowish spots or bright areas showing fine reflective cracks	Colours: pale green to pale yellow green, low intensity	/

Table 2. Organic petrology observation for the roe deer bones. The ID is formed by RO, which stands for the species, and a number, which stands for the temperature degrees.

ID	Colour	REFLACTANCE%R (at 546 nm)					OPTICAL PROPERTIES		Fat-derived char
		Interval	Mean	# meas.	Standard deviation	Histogram characteristics	Reflected white light	Fluorescence mode	
RO20	light grey	10 µm	0.097	100	0.068	Unimodal with rare outliers	Blurry and mostly bright surface, pale grey, yellowish-white, greyish-white, very light brown, bright whitish domains	Blurry and bright surface Colours: very pale green, bright yellowish-green, very low to low intensity	-
RO100	Light grey, whitish, yellowish	10 µm	0.164	115	0.143	Unimodal with a right skewed distribution and rare outliers	Blurry surface with variable brightness, pale grey, light grey to dull grey. Some domains are yellowish, whitish and very light brown	Blurry surface Colours: pale green, low intensity. Partly yellow-green along the bone edge	-
RO150	Greyish, whitish, Light brown	10 µm	0.362	109	0.281	Unimodal with a skewed distribution (right) and few outliers	Blurry and bright surface, light grey to middle grey. Dull grey-brown near the edge of the bone which shows fine cracks.	Blurry surface Colours: very pale green very low intensity. Partly yellow-orange along the bone edge	-
RO200	Greyish, light brown	10 µm	0.159	83	0.105	Unimodal with a skewed distribution (right) and one outlier	blurry surface, light grey-brown, grey-brown, brown-orange. Few very bright domains (high reflecting) showing whitish-yellow colour	Blurry surface Colours: very pale green, yellow-green, low to very low intensity	-

RO250	Light brown-orange	10 µm	0.184	95	0.131	Unimodal with a skewed distribution (right) and rare outliers	Blurry surface, pale grey-brown, orange-brown, light brown, reddish-brown. Some bright yellowish-grey domains show high brightness	Blurry surface Colours: pale green, brown-yellow, bright yellow-green, middle brown, orange-brown, very low to medium intensity	-
RO300	Dark brown, black	10 µm	0.21	122	0.13	Bimodal with a skewed distribution to the right and rare outliers	The bone structure is (granular and fibrous concentric bright lines around the haversian canals). Frequent bright fine cracks The bone matrix appears bright orange-brown, yellowish-grey and reddish-brown	Colours: yellow-green to bright green, medium to high intensity Some restricted domains including the edge of the bone show a brown and dark brown fluorescence of low to medium intensity	-
RO350	Black	10 µm	0.096	120	0.021	Narrow and unimodal	Middle grey (mostly near the edge of the bone), dark grey and grey-brown with reddish-orange internal reflections in most domains Fine cracks mostly perpendicular to the edge line affect the edge and the domains with internal reflections	Colours: yellow, yellow-green, dark green, middle brown to dark brown (near the edge), low to high intensity Near the edge of the bone the fluorescence intensity can be very low and some non-fluorescing domains are frequent	Rare thin char coating in some haversian canals

RO400	Black	10 µm	0.112	134	0.099	Unimodal with a skewed distribution to the right and rare outliers	The edge of the bone appears light grey to middle grey and is affected by numerous fine cracks The middle part of the bone is mostly dark grey with bright yellowish-orange domains showing numerous bright fine cracks Large irregular fissures run through the entire bone	Colours: generally bright green, bright yellow, yellow-brown, low to medium intensity Near the edge of the bone the fluorescence is dark brown (light grey domains in incident light) and few domains are non-fluorescing	Thin char coating in the haversian canals and locally along the bone edge
RO450	Dark-brown to reddish brown	10 µm	0.097	108	0.049	Unimodal with few outliers	The edge of the bone appears light grey to middle grey and is affected by numerous fine cracks The middle part of the bone is mostly dark grey, pale brown and brown-orange with bright yellow-brown and brown-grey domains showing numerous bright fine cracks	Colours: bright green, yellow-green, greenish-grey pale dark green, low to medium intensity Near the edge of the bone the fluorescence is dark brown	Thin char coating in the haversian canals and along the bone edge
RO500	Dark-brown to reddish brown	10 µm	0.121	100	0.121	Unimodal with a skewed distribution to the right and rare outliers	Blurry surface, pale grey, pale middle grey, pale grey-brown, pale orange-brown, pale orange Numerous cracks and pores with greyish fine granular zonation affect the entire bone. Yellowish bright spots or bright areas showing fine bright cracks	Colours: pale green to pale yellow green, low intensity. Rarely yellow-brown and brown	-

Table 3. Organic petrology observation for the Horse rib bones. The ID is formed by HO, which stands for the species, and a number, which stands for the temperature degrees.

ID	Colour	REFLACTANCE%R (at 546 nm)					OPTICAL PROPERTIES		Fat-derived char
		Interval	Mean	# meas.	Standard deviation	Histogram characteristics	Reflected white light	Fluorescence mode	
HO20	Light grey, brown	10 µm	0.095	144	0.145	Unimodal with a right skewed distribution and few outliers	Blurry and mostly bright surface Colours: pale grey, pale greenish-grey, yellowish-white, greyish-white, pale light brown, pale brown-grey, yellow-orange, bright whitish-grey domains	Blurry and bright surface Colours: pale green turquoise, bright yellowish-green, very low to low intensity	-
HO100	Light grey, light brown, reddish-brown	20 µm	0.504	162	0.598	Unimodal with a right skewed distribution and few outliers	Blurry surface Edge: light grey, bright whitish grey Main part: bright reddish-brown, orange-brown, light brown, pale dark brown, pale reddish-brown. Numerous bright spots	Blurry surface Colours: pale green, pale yellow-green, pale green-turquoise, bright yellow-green, pale yellow-brown, pale greyish-yellow, low intensity	-
HO150	Whitish, orange-brown	30 µm	0.156	122	0.155	Unimodal with a right skewed distribution and few outliers	Blurry surface Edge: whitish-grey, pale grey Main part: pale orange-brown, yellowish-white, pale reddish-orange, yellow-orange	Blurry surface Colours: pale green, pale yellow-green, yellow, greenish-yellow, low intensity	-
HO200	Whitish, reddish-brown	30 µm	0.314	127	0.260	Multimodal with few outliers	Blurry surface Edge: whitish-grey, pale grey. Main part: pale orange-brown, yellowish-white, pale	Blurry surface Colours: pale green, pale yellow-green, yellow, greenish-	-

							reddish-orange, yellow-orange	yellow, brown-yellow, low intensity	
HO250	Middle brown, reddish-brown	30 µm	0.819	100	0.626	Multimodal with few outliers	Blurry surface Edge: orange-brown Main part: bright yellow-orange, pale reddish-orange, dark grey and middle grey (heterogeneous granular and fissured domains)	Blurry surface Colours: pale green, dark yellow-green, dark yellow-brown, dark brown, reddish brown, dark orange-brown, low to medium intensity	-
HO300	Black	30 µm	0.298	155	0.178	Unimodal with a skewed distribution to the right and few outliers	Blurry surface. Edge: middle grey Main part: yellow-brown, orange-brown, bright reddish-orange, bright light orange, middle grey and light grey whitish (heterogeneous granular and fissured domains)	Blurry surface Colours: pale orange-brown, yellow-brown, yellow, bright green, dark brown, dark yellow-green, pale dark green, low to high intensity	-
HO350	Dark brown, black	20 µm	0.147	124	0.105	Unimodal with a right skewed distribution and few outliers	Blurry surface Edge: light grey, middle grey, porous, fissured Main part: yellowish-grey, bright orange-brown, yellowish-brown, reddish-orange, middle grey and light grey-yellowish (mostly fine granular excepted the homogeneous middle grey to black fillings in the haversian canals)	Very blurry surface. Colours: very dark greenish-brown (edge) brown, yellowish-brown, yellow-brown, yellow, bright green, greenish- brown, yellow-green, dark green, pale green, low to high intensity	Rare thin char coating (white) in some haversian canals

HO400	Black	20 µm	0.156	136	0.106	Unimodal with a skewed distribution to the right and rare outliers	Locally, blurry surface Edge: middle grey-brown, granular and porous Main part: dark grey with reddish internal reflections, orange-grey, bright orange, grey-brown, light grey (edge of some haversian canals)	Colours: very dark green, pale green, light green, pale yellow-brown, yellow-green, yellow low to high intensity In fluorescence mode, the immersion oil quickly becomes "cloudy" due to the probable incorporation of fatty substances from the bone	Thin char coating in some haversian canals (middle grey), in larger cavities and along the bone edge (light grey, white)
HO450	Black, grey	10 µm	0.114	100	0.152	Unimodal with few outliers	Blurry surface Edge: fissured, middle brown, light brown, pale orange brown Main part: bright orange-brown, pale grey-brown, bright spots. The edge shows mostly a pale grey, fine granular coating (altered char?)	Colours: light green, pale yellow-green, yellow-green, yellow, low to high intensity.	Rare thin char coating in some haversian canals (white)
HO500	Black, grey	20 µm	0.268	124	0.240	Multimodal with a skewed distribution to the right and few outliers	Blurry surface Edge: pale grey-brown Main part: orange-brown, pale grey-brown, pale reddish-orange, dark-grey-brown, bright domains and spots	Colours: light green, dark yellow-green, pale dark-green, dark brown-green, low to high intensity.	-

Table 4. Organic petrology observation for the Horse radio-ulna bones. The ID is formed by HOO, which stands for the species, and a number, which stands for the temperature degrees.

ID	Colour	REFLACTANCE%R (at 546 nm)					OPTICAL PROPERTIES		Fat-derived char
		Interval	Mean	# meas.	Standard deviation	Histogram	Reflected white light	Fluorescence mode	
HOU20	Light orange-brown	40 µm	0.036	101	0.011	Unimodal	Blurry Colours: mostly pale grey, pale greenish-grey, yellowish-white, greyish-white, pale light brown, pale brown-grey, bright whitish-grey domains	Blurry and bright surface Colours: pale green turquoise, bright yellowish-green, very low to low intensity	-
HOU100	Light brown, light orange-brown	30 µm	0.063	103	0.022	Unimodal	Blurry surface Edge: light grey, bright whitish-grey Main part: pale grey, withish-grey, pale orange-brown. Few bright spots	Blurry surface Colours: pale green, pale yellow-green, pale green-turquoise, bright yellow-green, low intensity	-
HOU150	Light brown, orange-brown	30 µm	0.051	108	0.014	Unimodal	Blurry surface Edge: whitish-grey, pale grey. Main part: pale grey, yellowish-grey	Blurry surface Colours: pale green, pale yellow-green, low intensity	-
HOU200	Light orange-brown, reddish-brown	30 µm	0.070	108	0.034	Unimodal with one outlier	Blurry surface Edge: brownish-grey, pale grey Main part: pale greenish-grey, yellowish grey, pale yellow-orange, bright whitish grey	Blurry surface. Colours: pale green, pale yellow-green, pale brown-yellow, low intensity	-

HOU250	Middle brown, reddish-brown	40 µm	0.128	101	0.045	Unimodal with a skewed distribution to the right	Blurry surface Edge: orange-brown Main part: yellowish-grey, pale orange-grey	Blurry surface Colours: pale green, pale yellow-green, pale brown-yellow pale reddish-brown, orange-brown, low to medium intensity	-
HOU300	Dark brown, black	30 µm	0.159	129	0.052	Unimodal with a skewed distribution to the right	Blurry surface Edge: middle grey-brown Main part: pale yellow-brown, orange-brown, bright reddish-orange, bright light orange, middle grey. Only few fissured domains	Blurry surface Colours: pale orange-brown, pale brown, yellow-brown, yellow, yellow-green, dark brown, dark yellow-green, pale dark yellow, low to high intensity The edge of the bone is partly non-fluorescing	Few thin char coating (middle grey, light grey) in some haversian canals and along the bone edge (middle grey, light grey) White oval and rounded small char bodies as inclusions in the char coating along the bone
HOU350	Black	40 µm	0.091	124	0.015	Unimodal	Blurry surface Edge: light grey, middle grey, white Main part: pale orange-grey, yellowish-grey, bright orange-brown, yellowish-brown, reddish-orange, middle grey and light grey-yellowish	Very blurry surface Colours: greenish-yellow, pale greenish-brown (edge), yellowish-brown, yellow-brown, yellow, low to medium intensity The edge of the bone is partly non-fluorescing	Thin char coating (middle grey, light grey, white) in some haversian canals and along the bone edge (middle grey, light grey,white) White and grey oval and rounded small char bodies as

									inclusions in the char coating along the bone
HOU400	Black	40 µm	0.100	116	0.066	Unimodal with few outliers	Blurry surface Edge: fissured, porous, dark grey-brown, rarely middle grey Main part: dark grey with orange internal reflections, orange-grey, bright orange, grey-brown, light grey (edge of some haversian canals)	Colours: very dark green, pale green, light green, pale yellow-brown, yellow-green, yellow low to high intensity In fluorescence mode, the immersion oil quickly becomes "cloudy" due to the probable incorporation of fatty substances from the bone	Thin char coating in some haversian canals (light grey, white) Homogeneous white and light grey char coating of variable thickness along the bone edge showing degassing pores and inclusions of dark grey micro fragments of bone The reflectance of the high reflecting white char reach 2,32 %Ro. That of the light grey char amounts to 0.84 %Ro
HOU450	Dark brown, black	40 µm	0.119	134	0.134	Unimodal with few outliers	Blurry surface Edge: fissured, middle brown, light orange-brown, pale orange-brown, dark grey Main part: bright orange-brown, pale grey-brown, dark grey, bright spots	Colours: light green, pale yellow-green, yellow-green, yellow, brown-green, pale dark green, low to high intensity	Thin char coating in some haversian canals (white) Homogeneous and fine heterogeneous white char coating of variable thickness along the bone edge showing large degassing pores

HOU500	Black	40 μm	0.140	128	0.124	Unimodal with a skewed distribution to the right and rare outliers	Blurry surface Edge: pale grey-brown Main part: orange-brown, pale grey-brown, pale reddish-orange, dark-grey-brown, bright domains and spots	Light green, dark yellow-green, pale dark-green, dark brown-green, low to medium intensity	Rare remains of thin char coating along the bone edge