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

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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

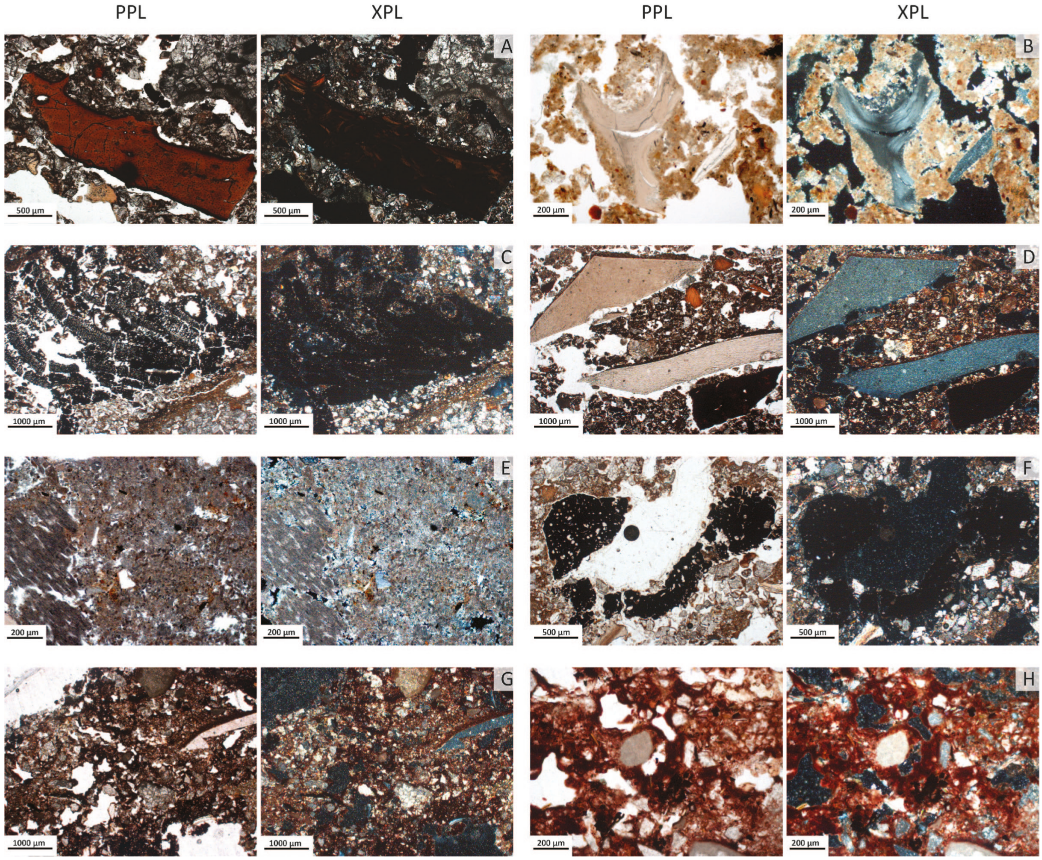

***Fig. 1** - Anthropogenic components, both in PPL (left) and XPL (right). (A) Burnt bone fragments (MM12, A9_SXII). (B) Calcine bone with embedded in a groundmass rich in calcite deriving from weathered ash (RF-19-31, A10IV_SVIII). (C) Charcoal fragment (MM13, A2 S16). (D) Micro-debitage flakes of 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

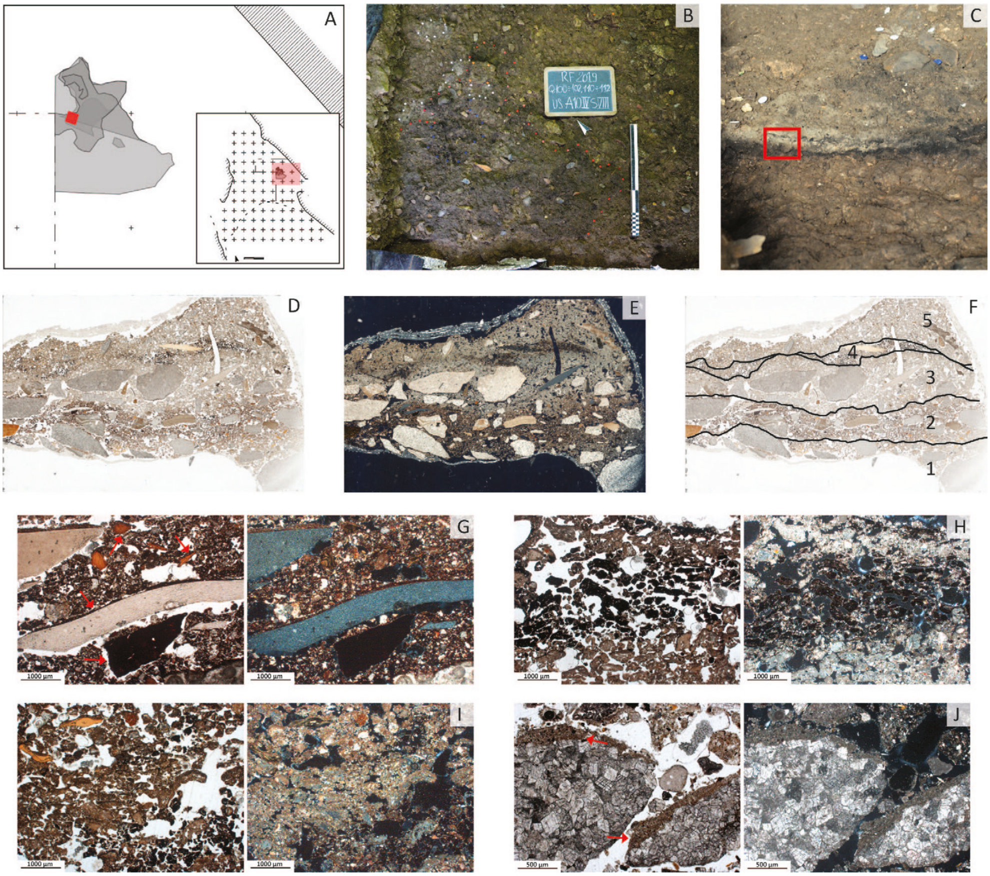

***Fig. 2** - (A) Location of the feature A10IV_SVIII and sample RF-19-31 (red squares). (B) and (C) Field photos in top view and profile. The feature's profile exhibits alternating sub-layers (grey and black), detectable in thin section. (D), (E) and (F) Thin section scans (RF-19-31) in PPL, XPL, and 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

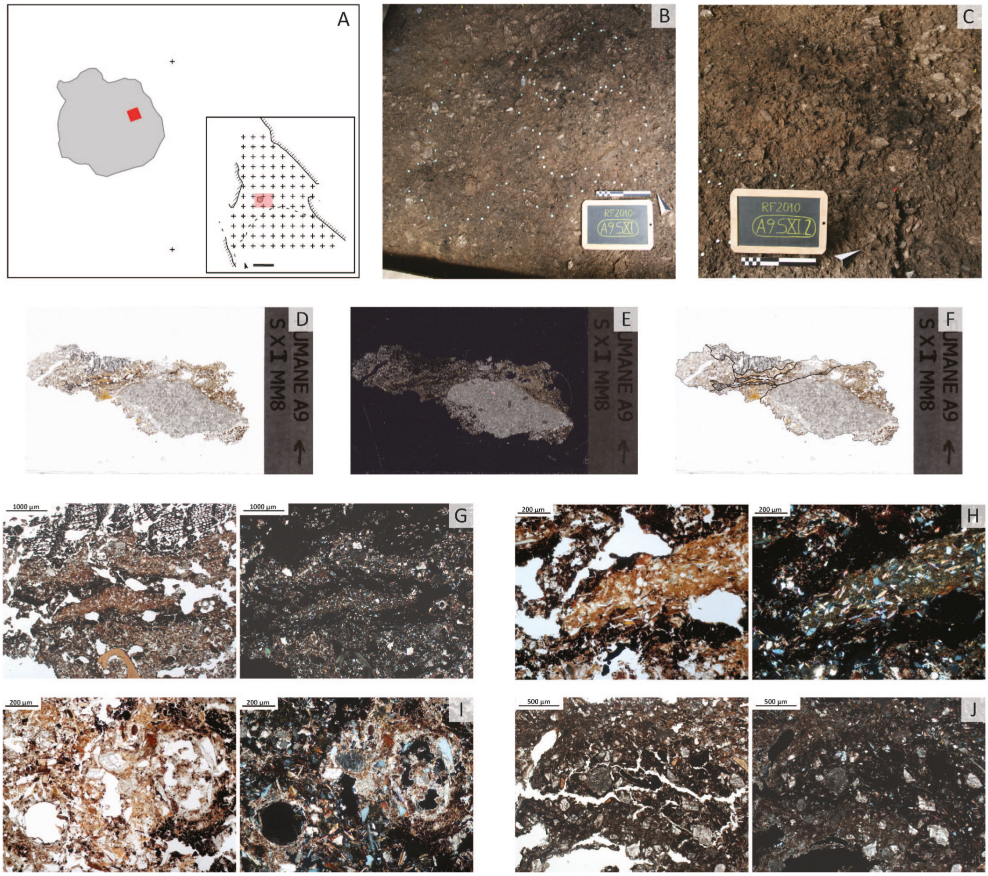

***Fig. 3** - (A) Location of the feature A9_SXI and sample MM8 (red square). (B) and (C) Field photos in top view and profile. (D), (E) and (F) Thin section scans (MM8) in PPL, XPL, and micro-unit subdivision. The groundmass exhibits a close porphyric c/f-related distribution, with the geogenic coarse 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

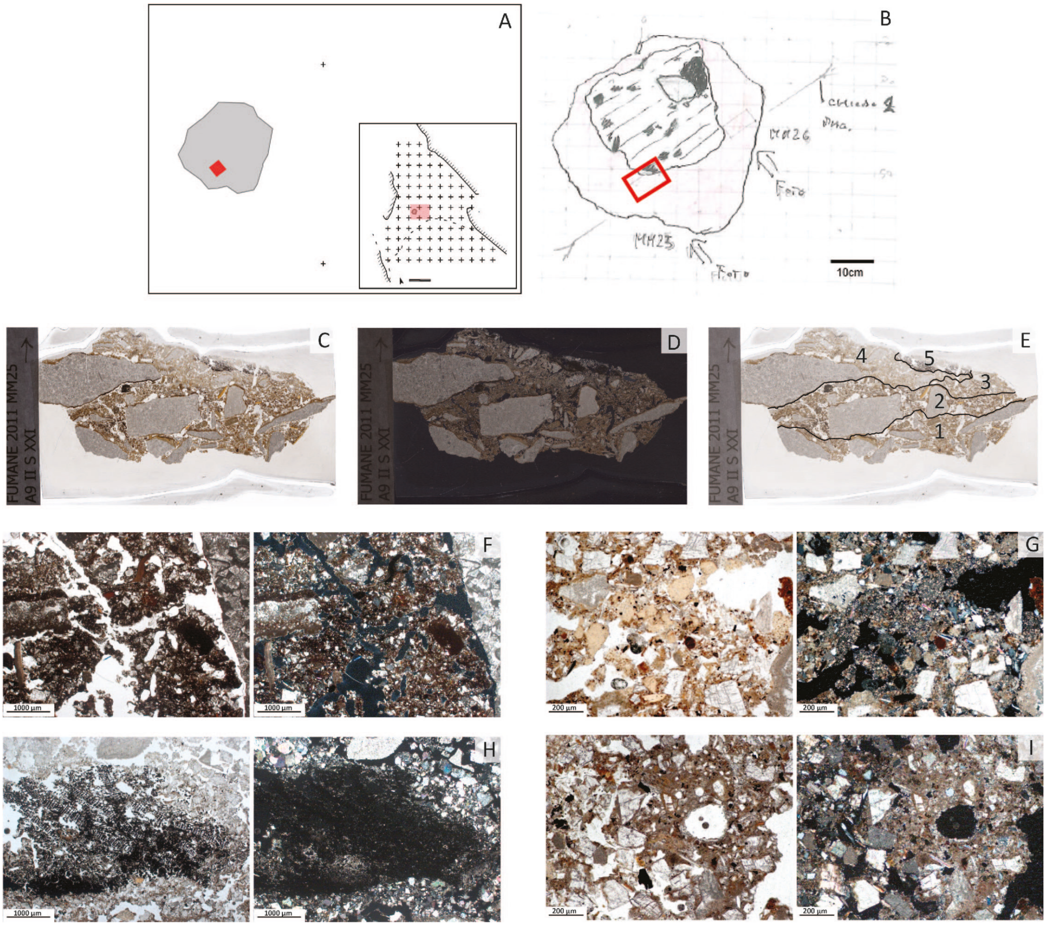

***Fig. 4** - (A) Location of the feature A9II_SXXI and sample MM25 (red square). (B) Report drawing. (C), (D), and (E) Thin section scans (MM25) in PPL, XPL, and micro-units subdivision. Voids are more or less homogeneous along the thin section, these are mainly vughs and channels, with very few vesicles. 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

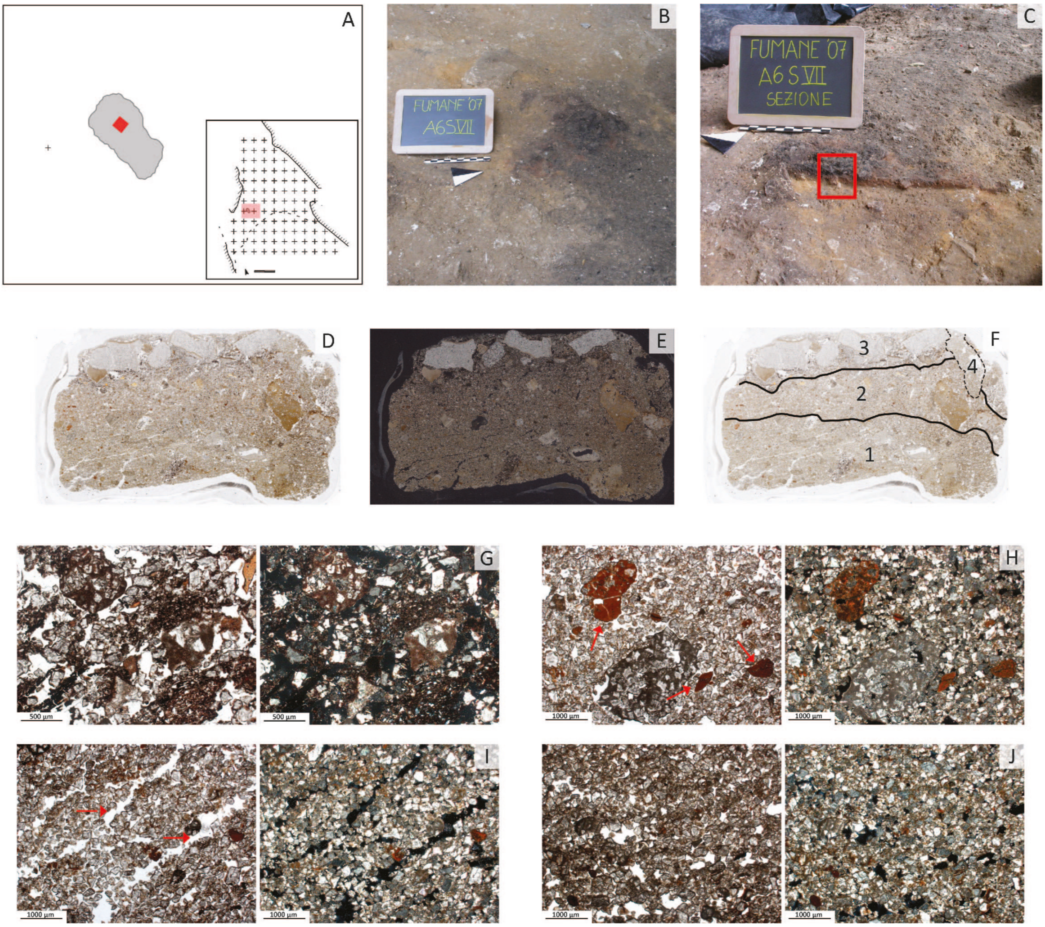

***Fig. 5** - (A) Location of the feature A6_SVII and sample MM34 (red square). (B) and (C) Field photos in top view and profile. (D), (E), and (F) Thin section scans (MM34) in PPL, XPL, and micro-unit subdivision. Note that the thin section includes three different micro-units (the 4 is a borrow). The 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

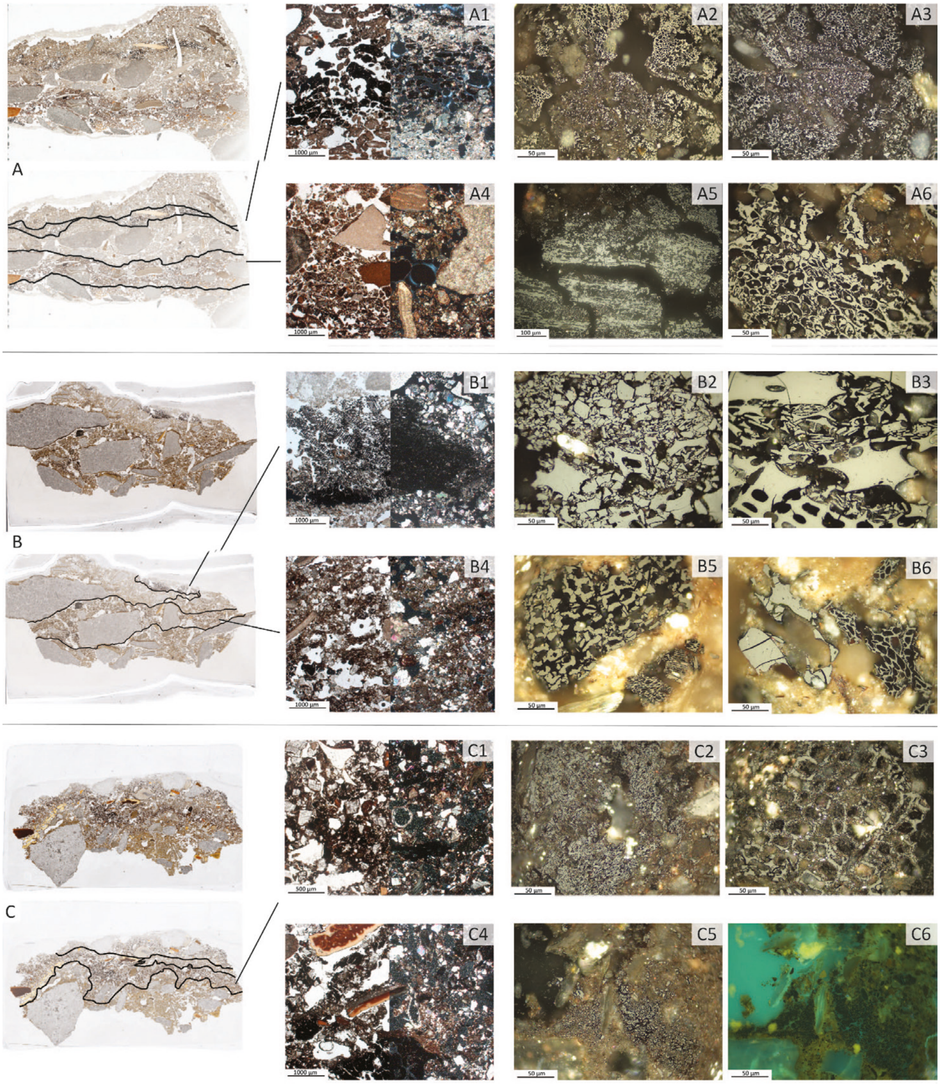

***Fig. 6** - Organic petrology analysis (incident white light, oil immersion) of samples RF-19-31, MM25, MM31. (A) RF-19-3 form A10 SVIII. (A1) and (A4) Micromorphological overview of the upper and lower organic layer (PPL and XPL). (A2) and (A3) Detail of collapsed tiny herbaceous-derived charcoal 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.*

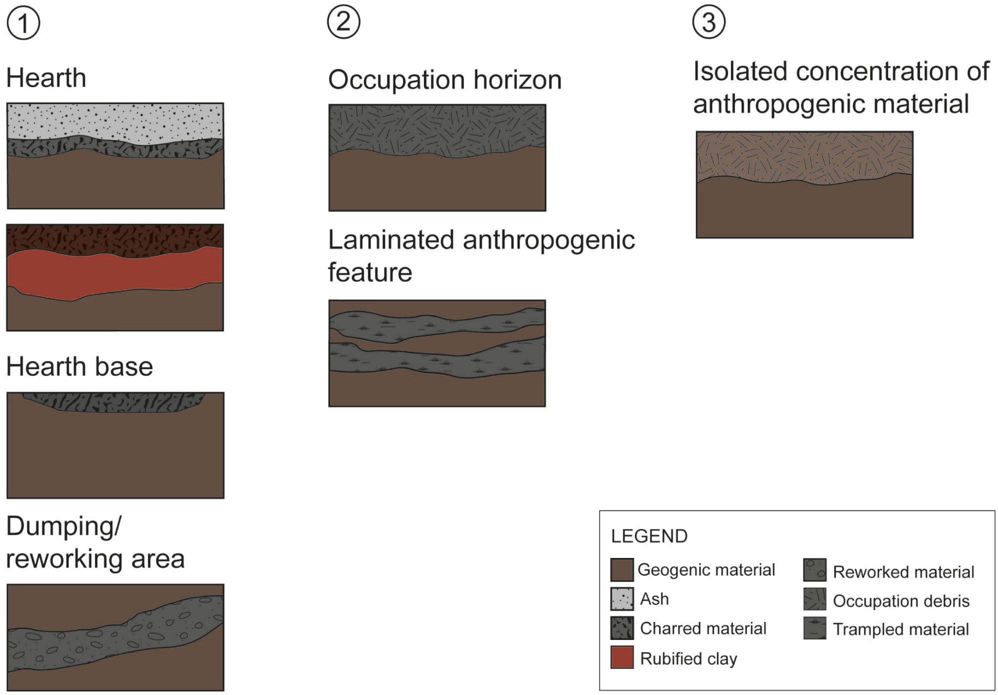

***Fig. 7** - Micromorphological classification system. (1) Shorter-term event group, Hearths, hearths base, and dumping/reworked area. (2) longer-term event group. Occupation horizon and laminated anthropogenic feature. (3) Isolated concentration of anthropogenic material.*

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).

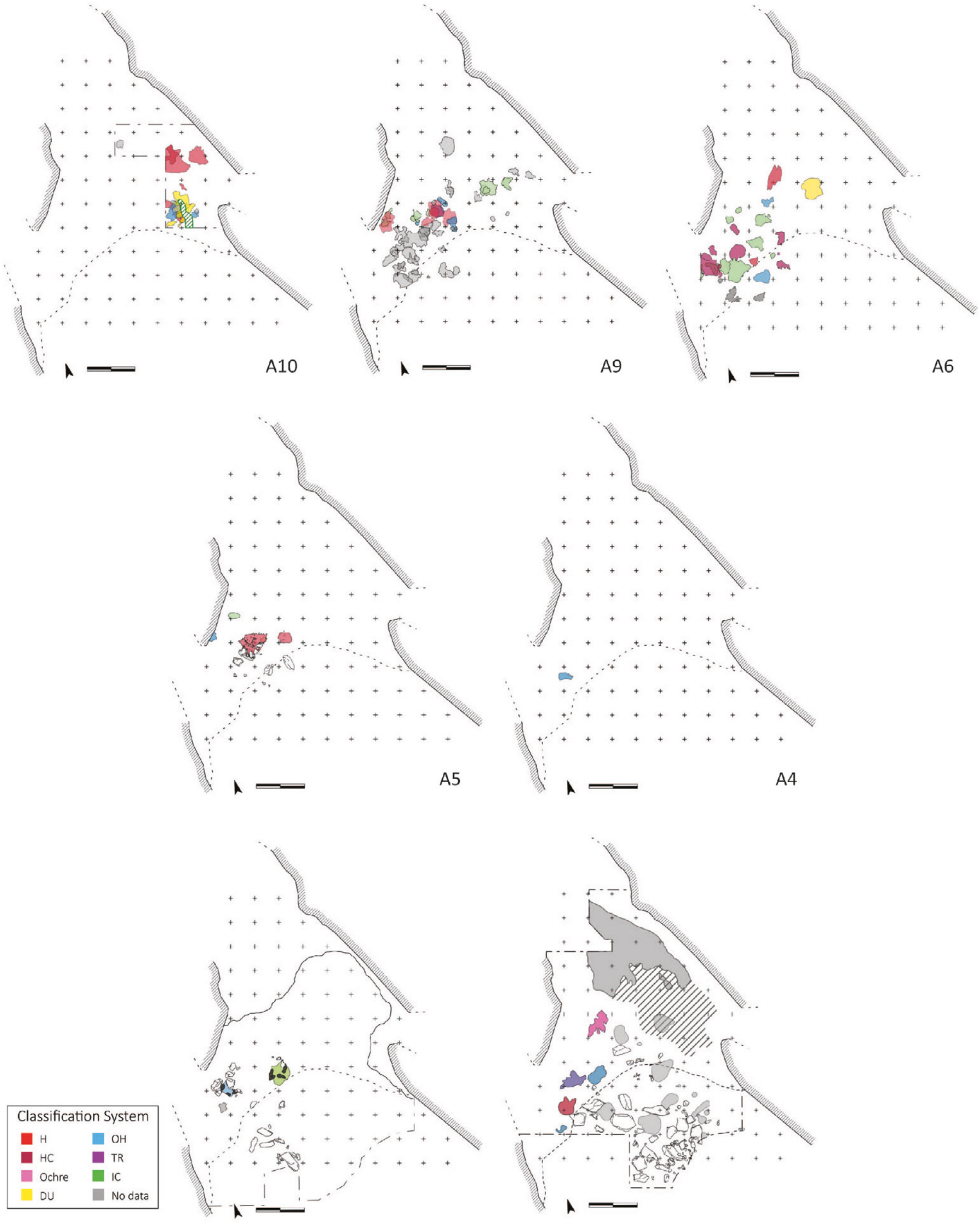

***Fig. 8** - Site maps of Fumane Cave showing the spatial distribution of the features by layers (A10, A9, A6, A5, A4, A3, and A2). Hearth (H) in red; hearth with change in clay colour (HC) in burgundy; ochre feature in pink; dumping/reworking area (DU) in yellow; occupation horizon (OH) in blue; laminated 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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