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RESEARCH

Was fire use a cultural trait of the Gravettian? New micro-archaeological data from Fuente del Salín cave (Val de San Vicente, Cantabria)

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Abstract

Micro-archaeological data from sites located in central and eastern Europe show that, in comparison with other Upper Paleolithic hunter-gatherers, Gravettian foragers used fire more intensively and for a wider range of purposes. At these sites, this shift in pyrotechnology overlaps with the onset of periglacial conditions. Gravettian occupations of non-periglacial regions have been poorly investigated with micro-archaeological methods, and it remains to be further demonstrated whether these foragers also made a similar intensive and multipurpose use of fire. To further investigate this topic, we studied the sequence preserved at the cave of Fuente del Salín, in Cantabria, where previous excavations unearthed potential fire residues of Gravettian age. Using micromorphology, μ-X-ray fluorescence, and Scanning Electron Microscopy we reconstructed multiple phases of human visits to the site. Our results show that, during the main Gravettian occupation, foragers made intensive use of fire, as indicated by abundant heated bones and seashells, charcoals, amorphous char, fat-derived char, and in situ remains of potential stacked open hearths as well as burnt grass beddings. The intensive burning, systematic reuse of combustion features, and multiple purposes of the fires at Fuente del Salín are comparable with Gravettian sites from central and eastern Europe, indicating that these fire-use behaviors probably do not reflect a regional adaptation to periglacial environments but a cultural trait of the Gravettian tradition across Europe.

Keywords Pyrotechnology · Gravettian · Site-formation · Micromorphology · μ-XRF · SEM–EDX

Introduction

The ability to use fire at will is a hallmark of the genus *Homo*. For this reason, most studies have focused on identifying the earliest evidence of this behavior (Berna et al. 2012; Hlubik et al. 2017). More recently, researchers started focusing on how the technology behind making and exploiting fire, also known as pyrotechnology, evolved into other aspects of material culture (Bentsen 2014; Bentsen and Wurz 2019; Murphree and Aldeias 2022). Murphree and Aldeias (2022) proposed that Gravettian foragers changed the intensity, form, and function of modern human fire use, suggesting that Gravettian populations, compared to early periods in the Upper Paleolithic, used a wider range of combustion feature types, including fire installations, baked clay, and loess objects, particularly in the Middle Danube region. Furthermore, the elaboration of potentially symbolic elements such as anthropomorphic figurines is linked to a remarkable behavioral change in Anatomically Modern Humans (AMH) (Vandiver et al. 1989).

However, research on Gravettian fire use has been biased toward sites west of the Pyrenees, where the period overlapped with the onset of periglacial environments (Barbieri et al. 2021; Maier 2017; Murphree and Aldeias 2022). At Dolní Věstonice I-II (Czech Republic), Gravettian groups experienced significant climatic oscillations driven by

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Dansgaard-Oeschger events. Charcoal and pollen analyses indicate the presence of cold-tolerant conifers and deciduous trees, which facilitated semi-permanent occupations due to relatively high primary productivity (Beresford-Jones et al. 2011). Nonetheless, narrow tree rings suggest unfavorable growth conditions, underscoring the challenges these groups faced (Opravil 1952). Similarly, Grub-Kranawetberg (Austria) was characterized by cold, dry tundra-steppe ecosystems that supported megafauna like mammoths, with fire playing a crucial role in human survival under extreme conditions (Bosch et al. 2011). At Ságvár Lyukas Hill (Hungary), palaeoecological data indicate human occupation during the cold phases of the Last Glacial Maximum (LGM), with environmental shifts over tundra patches (Bösken et al. 2018). Předmostí (Moravia), situated near warm springs and animal migration routes, exemplifies how Gravettian groups strategically inhabited regions despite harsh conditions, demonstrating their resilience and adaptability to fluctuating climates (Musil 2010).

Therefore, it remains difficult to demonstrate whether this change in pyrotechnology can be truly regarded as a cultural trait characteristic of the Gravettian tradition or, conversely, as an environmental adaptation. To tackle this, Gravettian fire use needs to be better investigated in other regions that did not experience periglacial environments, such as Cantabria. In this region, the environmental conditions during the Gravettian were in general cold and dry, with wide regional variations, but not as harsh as in northern and central Europe. Most of the archaeological sites in the region are located close to the coast. Aside from rare remains of steppe bison, faunal evidence from Morín cave suggests temperate conditions (Bradtmöller 2015). Cave sites like Aitzbitarte III (Altuna et al. 2013) and El Mirón (Marín-Arroyo et al. 2023) highlight predominantly open and cold environments with scattered pines, junipers, and birches. Contrarily, the open-air site of Ametzagaina (Calvo et al. 2011) indicates a milder climate, with a more significant presence of deciduous trees like *Alnus* and *Corylus*.

Although hearths have been reported from multiple Gravettian sites throughout Iberia (Aubry 1998; Badal et al. 2019; Bradtmöller 2015; Brugal 2006; Fullola et al. 2012; Gaspar et al. 2016; Gutiérrez-Zugasti et al. 2012; Lucena et al. 2012; Sanchez-Martínez et al. 2021; Sellami 2009; Villaverde et al. 2021; Yravedra et al. 2017), only a handful of them has been investigated with micro-archaeological methods to confirm their anthropo- and pyrogenic nature (Angelucci et al. 2018). Furthermore, only Badal et al. (2019), Villaverde et al. (2021), and Yravedra et al. (2017) in Spain, and Sellami (2009) in Portugal, explored in-depth the pyrotechnology of Gravettian foragers.

The cave of Fuente del Salín, in Cantabria, is worldwide renowned for its rock paintings, consisting of negative and positive handprints (Alonso Gutiérrez 2018; Fernández-Navarro et al. 2022; González-Morales and Moure Romanillo 2008; Moure Romanillo et al. 1985). The site also preserved a Gravettian deposit dating between 26 to 29 ka calibrated Before Present (ka cal BP), and consisting of a dark layer, interpreted by the excavators as a hearth (González-Morales and Moure Romanillo 2008). Previous research at the site focused on the cave paintings, personal ornaments, and the technology used to create them (Alonso Gutiérrez 2018; Cuenca-Solana et al. 2013; Fernández-Navarro et al. 2022; González-Morales and Moure Romanillo 2008; Moure Romanillo et al. 1985). Furthermore, the study of bone and shell assemblages allowed to reconstruct the diversity of subsistence solutions exploited by Gravettian foragers, such as deer hunting, river fishing, and sea shell harvesting, which were favored by the proximity of the cave to coastal and estuarian environments (Blanco-Lapaz et al. 2023; González-Echegaray 2020; Gutiérrez-Zugasti et al. 2012). Contrarily, the potential fire residues preserved at the site remained uninvestigated. In this study, we present micromorphological, micro-X Ray Fluorescence (μ-XRF), and Scanning Electron Microscopy (SEM–EDX) data, to reconstruct fire use at the site and discuss the implications of our results for the study of Gravettian pyrotechnology. Furthermore, we analyzed the whole stratigraphy of the site to have a full diachronic overview of the sequence, and to better tease apart forager behaviors from geogenic processes.

Material and methods

Fuente del Salín

Cave Geology

Fuente del Salín is located 15 m above current sea level at its modern entrance, in the town of Val de San Vicente (northern Cantabria), near the Tina Menor estuary and at 3 km from the current coastline (Fig. 1a). The cave, formed under phreatic conditions, comprises two galleries connected by a sub-vertical passage (Fig. 1b-c). The modern entrance to the cave is located at the end of the lower gallery, which, unlike the upper dry passages, is currently situated in the epiphreatic zone, allowing only seldom access to the site. The original entrance, located at the end of the upper gallery, is estimated to have measured 1.84 m in height and 3.02 m in width, and situated at 7.48 m from the excavation, was blocked by a large ceiling collapse, shortly after 29 ka cal BP (González-Morales and Moure Romanillo 2008).

The cave system is hosted within limestone beds and calcarenites of Paleogene and Upper Cretaceous age. The limestone beds exhibit low compaction and weather into flakes, especially in the upper gallery where the archaeological excavation is located (Portero García and Ramírez

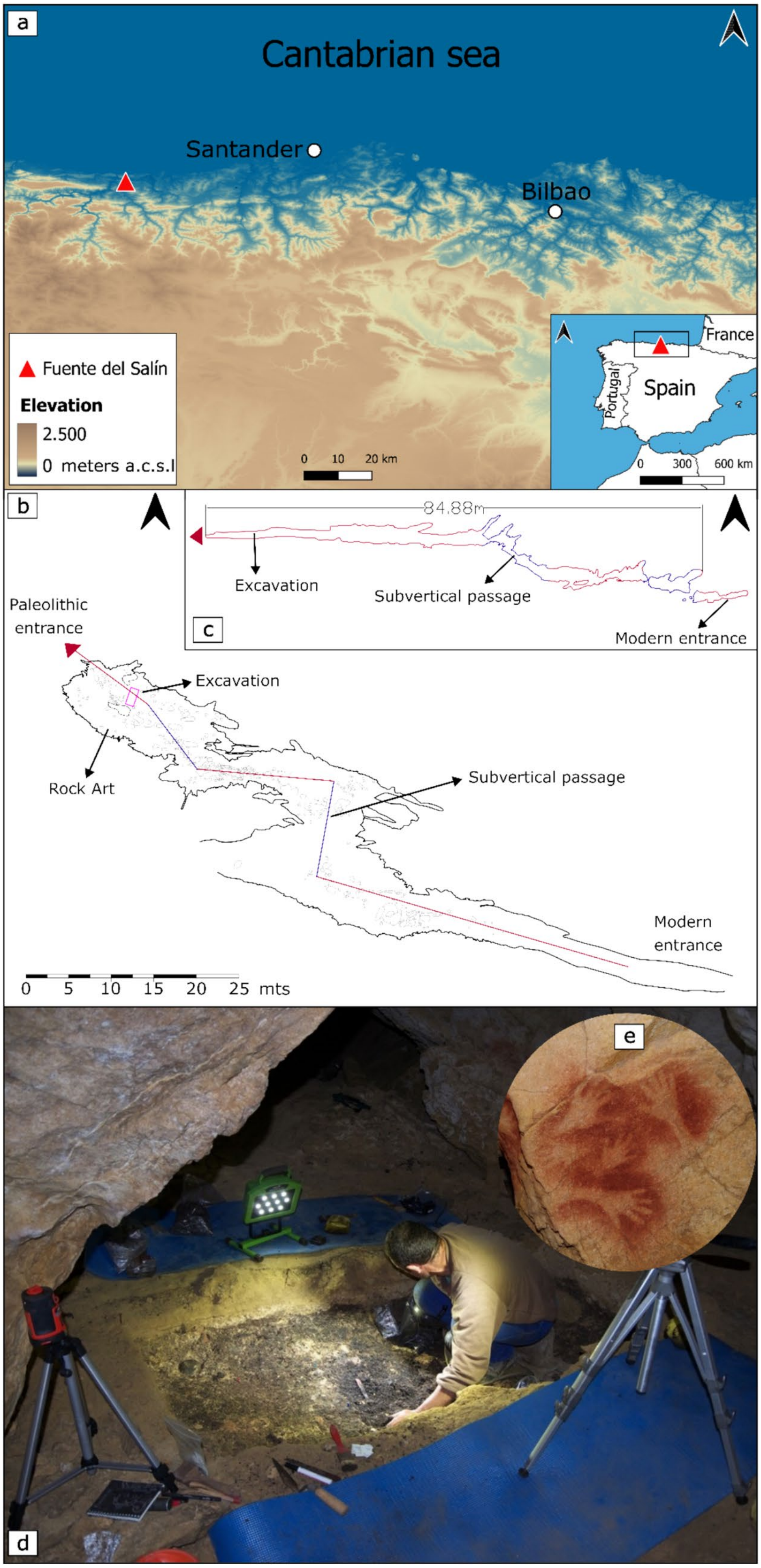


Fig. 1 **a** Elevation model of the Cantabrian region with the location of Fuente del Salín cave. **b** Plane of the cave which locates the excavation, rock art, and the modern and paleolithic entrances. A line indicates the path from the modern entrance to the Paleolithic entrance, divided into red and blue sections. **c** Longitudinal section of the cave, displaying the topography and representing the same path as shown in (b), providing an alternative view of the cave's structure. **d** Excavation inside the cave. **e** Negative red handprints inside the cave associated with the Gravettian foragers

del Pozo 1976). Sediment remnants along the cave walls and ceilings indicate that the cave underwent multiple phases of infilling and erosion.

Archaeological research

Cave paintings and surface archaeological materials in Fuente del Salín were first discovered in 1985 (Roldán et al. 1985; Moure Romanillo et al. 1985). In 1990–91 and 2000–03, archaeological surveys and excavations were conducted at the back of the upper gallery, close to a series of cave paintings and near the original entrance to the site (Fig. 1e) (Morales and Romanillo 2000; González-Morales and Moure Romanillo 2008).

During these efforts, researchers dug a 2m x 1m trench (Fig. 1d), comprising excavation squares K6 and L6, and exposed a stratigraphic sequence in which they distinguished three main units (Levels). The uppermost layer, Level 1, was subdivided into an upper layer of dark clay which is microlaminated at the bottom (Level 1.1), a speleothem crust (Level 1.2), and a soft speleothem crust, which the excavators classified as a *gour* (Level 1.3) (González-Morales & Moure Romanillo 2008). Level 1.1. showed rare, reworked archaeological material, that likely eroded from a higher passage located at 4.95 m from the excavation to the northeast, and approximately 7.30 m from the Paleolithic entrance to the cave.

Level 2 exhibits alternating laminations of reddened clay and charcoals with abundant fragments of fish bones and sea shells, which the excavators interpreted as a potential hearth (Gutiérrez-Zugasti et al. 2012, p. 419). Below this feature and covering the cave floor, Level 3 was described as a clay layer archaeologically sterile.

Bayesian modeling of radiocarbon ages from charcoal, faunal bones, faunal tooth, and seashells in Level 2, besides surface bones, allows to securely date human visits to Fuente del Salín to the Gravettian and places the formation of this layer between approximately 26 and 29 ka cal BP (Blanco-Lapaz et al. 2023; González-Morales & Moure Romanillo 2008). A charcoal sample from a rock art panel was dated to 22,2 ka cal BP. This sample, however, remained exposed and might have been contaminated with younger carbon input. The anthracological remains of Level 2 are currently under study by Monica Ruiz Alonso (Consejo Superior de Investigaciones Científicas, Madrid).

Micromorphology

To reconstruct site formation processes and investigate lateral variability in the composition and thickness of Level 2, we collected block samples for archaeological soil and sediment micromorphology analysis. The samples were taken from two stratigraphic profiles exposed during previous excavations inside Fuente del Salín, to cover the whole stratigraphic sequences: L6 east and K6 west (Fig. 2). A total of six blocks were retrieved (MM-1.1, MM-1.2, and MM-1.3 from K6 west and MM-2.1, MM-2.2, and MM-2.3 from L6 east), which were dried, impregnated with a resin mixture (70% epoxy resin, 30% styrene, and 5 mL of catalyst), cut and polished into six thin sections of 10 × 5 cm. The thin sections were scanned on a flatbed scanner at 1200 dpi in reflection mode. After, the slides were studied in Plain Polarized Light (PPL), Cross-Polarized Light (XPL), and Oblique Incident Light (OIL), using a petrographic microscope (Nikon Optiphot DIC Phase Contrast Dark Field).

Terminology and description of micromorphological features were made based on Stoops et al. (2010); Stoops (2020). For specific anthropogenic input, we based our interpretation on Karkanas and Goldberg (2018), Nicosia and Stoops (2017), Goldberg et al. (2001) and Goldberg and Macphail (2006).

μ-XRF

We conducted μ-XRF analysis (Fernández-Palacios et al. 2023; Mentzer 2017) on the six impregnated block samples collected from Fuente del Salín. A Bruker M4 Tornado was used to map the following elements: Al, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Si, Ti, and Zn. Data were acquired under 20 mbar pressure using both detectors, beam power of 30 W (tube voltage of 50 kV and tube current of 299 μA), a spot size of ~ 20 μm, and a spacing of point of 8–60 μm depending on the desired resolution. Dwell times per pixel of 10 ms up to 100 ms were used. Elemental maps were only analyzed qualitatively (presence/absence and spatial distribution of elements). The μ-XRF mappings were performed after thin section production, therefore the resulting images are slightly different from the corresponding thin section scans.

SEM–EDX

High-magnification imaging within targeted areas of block samples was achieved using a Scanning Electron Microscope equipped with an electron probe for X-ray microanalysis (EPMA) (Wilson 2017). Only the block sample MM-1.2 was analyzed, considering that we were interested in obtaining high-magnification images in Level 1.3. The latter corresponded initially to a soft speleothem crust, but after micromorphological observations, we realized it was a calcareous tufa, which was expected to be composed of carbonates and organic materials such as algae, mosses, and bacteria, components that we could not study under the petrographic microscope. Before the analysis, a sub-sample of MM-1.2 was cut, given the small size of the chamber of the equipment used in this study, and covered with a thin layer of gold, to improve conductivity and thus obtain better results.

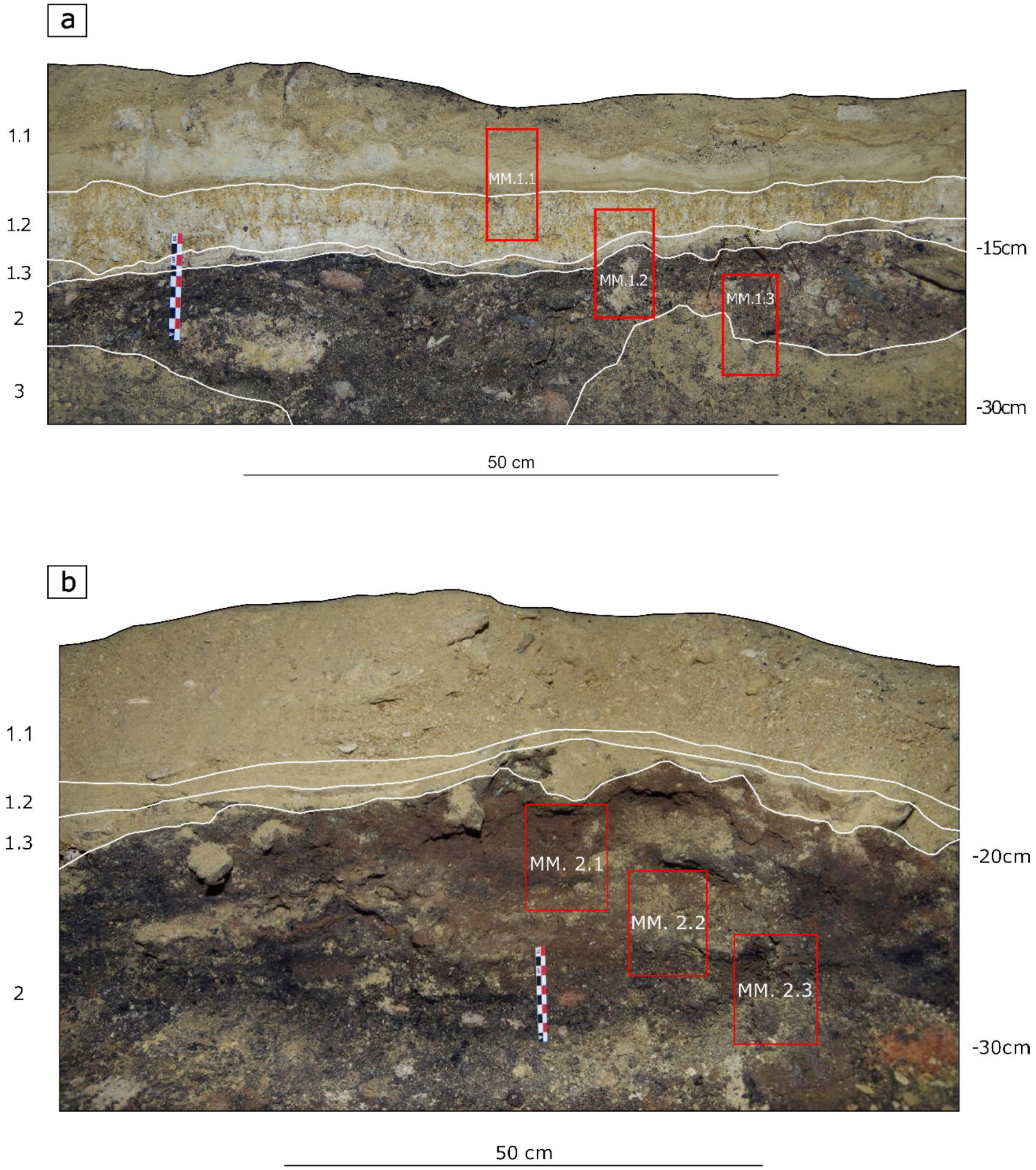


Fig. 2 Stratigraphic profiles K6 west (**a**) and L6 east (**b**). White lines indicate the contacts between Levels, which are labeled on the left side of the profile photos. Red rectangles depict the location of micromorphological samples

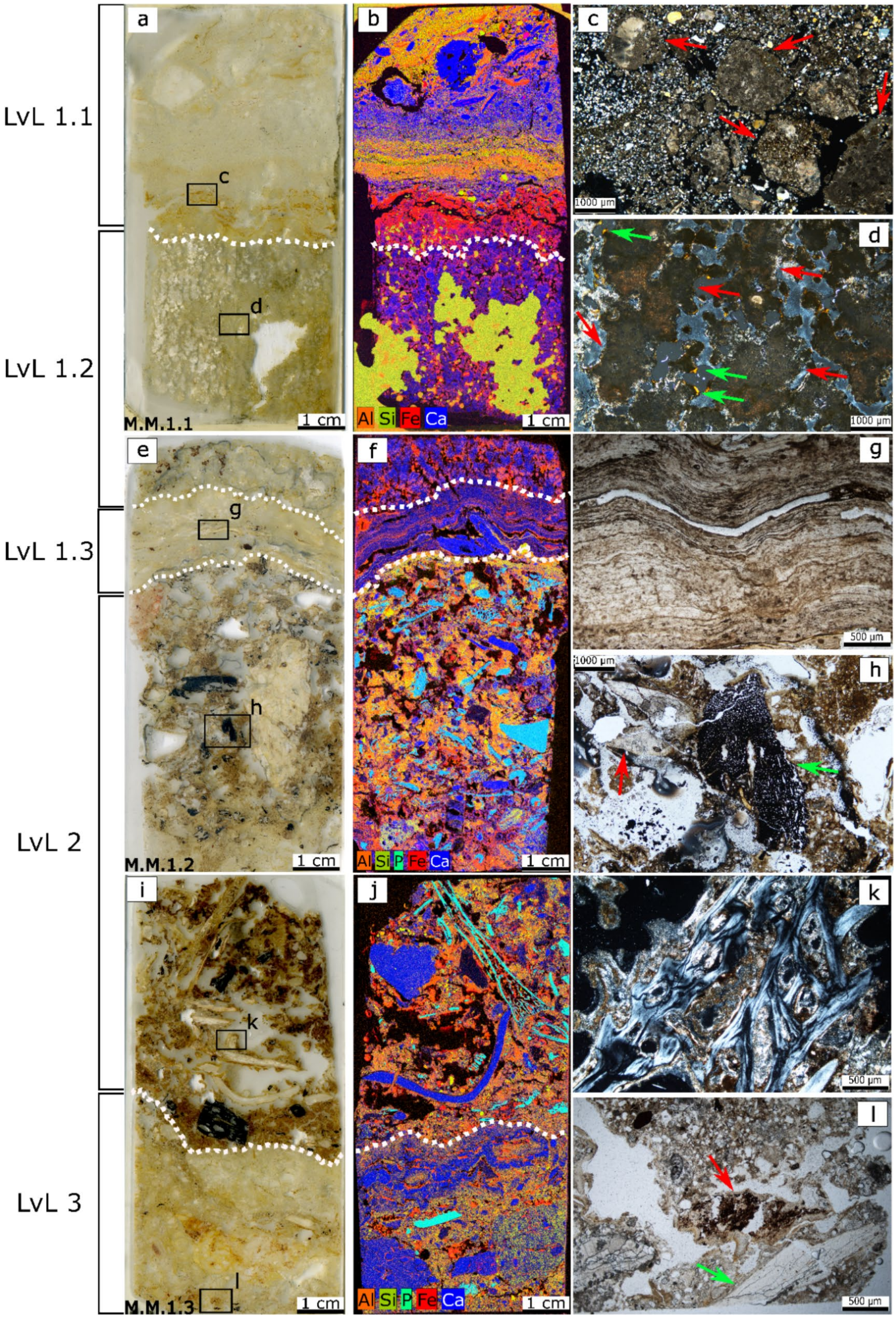
Results

Level 3

This unit is rich in fresh fossiliferous limestone grains, iron nodules, quartz, and calcite sand, including needle-fiber calcite, and clays (Figs. 3l and 4l). It has a crumbly microstructure, with dense spheroidal micritic carbonate aggregates. During thin section analysis, we identified rare potential archaeological materials, such as bones and charcoals (Fig. 3i-l).

Level 2

This level is rich in comminuted organic matter, fat-derived char (Fig. 5b), ashes in the form of rhombic and micritic pseudomorphs of calcium oxalates (Karkanas 2021), as well as poorly sorted and randomly oriented fragments of bone (Figs. 4c-f-k and 5d-f), charcoal, seashells, and


LvL 1.1
LvL 1.2
LvL 1.3
LvL 2
LvL 3
a
b
c
d
e
f
g
h
i
j
k
l
M.M.1.1
M.M.1.2
M.M.1.3
1 cm
Al Si Fe Ca
Al Si P Fe Ca
1000 µm
500 µm

◂**Fig. 3** Stratigraphic sequence in the west profile of square K6. White dashed lines show the contact between levels. **a** Scan of thin section MM-1.1. **b** µ-XRF elemental mapping of block sample MM-1.1. **c** Photomicrograph in XPL from Level 1.1 depicting calcitic-crystallitic micromass with abundant well-sorted quartz grains, and spheroidal micritic aggregates (red arrows). **d** Photomicrograph in XPL from Level 1.2 showing dense micritic aggregates (red arrows) and iron-rich clays coating the aggregates (green arrows). **e** Scanned thin section MM-1.2, showing the contact between Levels 1.3 and 2. **f** µ-XRF elemental mapping of block sample MM-1.2 displaying the passage from the calcium-rich Level 1.3 (Ca in dark blue) and bone-rich Level 2 (P in light blue). **g** Photomicrograph in PPL depicting lamellar micritic and sparitic spongy fabrics characteristic of calcareous tufa from Level 1.3. **h** Photomicrograph in PPL displaying randomly oriented charcoals (green arrow) and heated bones (red arrow) from Level 2. **i** Scan of thin section MM-1.3, illustrating the passage from Levels 2 to 3. **j** µ-XRF elemental mapping of the block sample MM-1.3 showing larger and more frequent bones (P in light blue) and shells (Ca in dark blue) than MM-1.2, from Level 2, as well as very rare bones in Level 3 (P in light blue). Images (i) and (j) are mirrored. **k** Photomicrograph in XPL showing a fish bone coated by calcium carbonate in Level 2. **l** Photomicrograph in PPL showing bones (green arrow) and char (red arrow) from Level 3

knapped lithic artifacts (Fig. 5c). Heated bones (75%) were identified based on their poor osteon preservation in XPL, and a pale grey to dark-brown color in PPL (Figs. 4c-k and 5f) (Villagran et al. 2017a). Some of the bones exhibit in situ fractures, indicative of trampling (Fig. 4c and 6a-b, Online Resource 1e) (Miller et al. 2010; Nicholson 1992; Rentzel et al. 2017). Bone fragments also show incipient tunneling due to bacterial and fungi activity (Brönnimann et al. 2018; Durand et al. 2010) and staining by iron and manganese oxides (Online Resource 1e-f) (Shahack-Gross et al. 1997). Faunal remains were not identified taxonomically with the micromorphological analysis; however, based on the work of Blanco-Lapaz et al., (2023) and González-Echegaray (2020) they must belong to fish (Fig. 3k), predominantly salmonids, and ungulates such as red deer and Iberian ibex. Rare fragments of seashells and bones exhibit partial replacement by secondary carbonates (Online Resource 1b-c) and incipient dissolution (Online Resource 1g-h).

Our micromorphological analysis revealed that Level 2 in the west profile of square K6 is extensively disturbed by post-depositional processes, such as bioturbation, dumping, rake-out (Fig. 6c-e), trampling, and secondary carbonate formation (Figs. 5, 7 and Online Resource 1a-b). In this area, we found that Level 2 displays combustion features like ashes, fresh and heated bones, charcoal, shells, and rubified clay aggregates in a chaotic arrangement. These features have been associated with dumping and rake-out processes (Banerjea et al. 2015; Mallol et al. 2013; Miller et al. 2010).

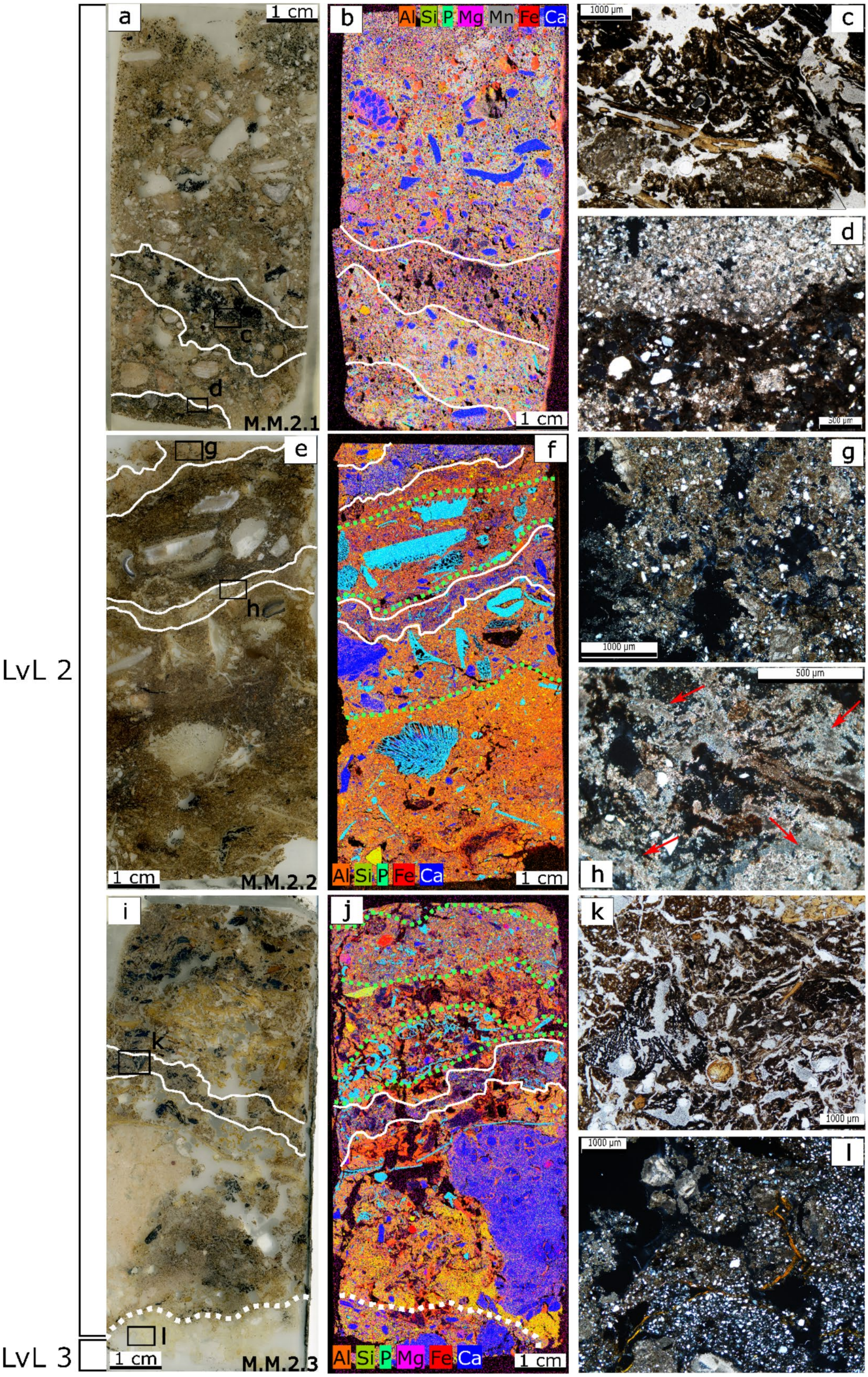
Level 2 exhibits better preservation in the east profile of square L6, where we observed horizontal, stacked, and microlaminated layers, which have thicknesses from 500 µm to 0.5 cm, and extend horizontally by up to 4 cm (Fig. 7a-g). These laminations can be grouped into four separate microfacies (MF). MF1 is composed of endokarstic sediment mixed with dumped materials, such as amorphous organic matter, rubified clay aggregates, as well as fresh and heated bones, which occasionally exhibit evidence of trampling (Fig. 7c1, g1). MF2 is made from articulated, cemented, and recrystallized ashes (Fig. 7c-d-g-h) (Canti 2003; Karkanas 2021; Villagran et al. 2017b). MF3 exhibits exclusively heated and charred residues, such as ash, burnt bones, charcoals, and fat-derived char (Fig. 7g-h) (Berna and Goldberg 2007; Goldberg et al. 2009). In MF3 we also identified features comparable with the stringers that have been reported from Middle Stone Age deposits at Sibudu, Border Cave, and other sites in South Africa, which were interpreted as grass beddings subsequently burned by foragers during sanitization activities (Fig. 5a) (Goldberg et al. 2009; Miller and Sievers 2012; Sievers et al. 2022; Wadley et al. 2020, 2011). MF3 occasionally displays high amounts of iron (7.9%) and manganese (11.4), as evidenced by µ-XRF analysis of block sample MM-2.2 (Fig. 7a-b). MF4 is characterized by endokarstic sediment without any organics or human input. When this sequence of microlayers is present, we identified preserved combustion structures, characterized by articulated ashes. Our micromorphological analysis revealed that the MFs recur often in a specific order, with the geogenic-rich MF1 at the bottom, the ash-rich MF2 in the middle, the burnt-residues-rich MF3, and the endokarstic sediment microlayer on top MF4 (Figs. 4e-f and 7).

Level 1.3

This unit is composed of a calcitic-crystallitic b-fabric, with laminated micritic and microsparitic calcium carbonate. These laminations display alternations between dense and massive, to light and spongy microstructures, as well as calcified colonies of bacteria. These features are associated to the seasonal growth of algae and are all diagnostic for tufa deposits (Figs. 3e-g and 9a-d) (Ajuaba et al. 2021; Canora et al. 2023; Chafetz and Folk 1984; Dabkowski 2014; Simöes 2019; Oste et al. 2021; Pentecost 2005b; Perri et al. 2012; Suchý et al. 2019). In agreement with our micromorphological observations, SEM–EDX analysis revealed the occurrence of stacked algae and mosses as well as abundant calcified algae and bacteria filaments (Fig. 9e-f) (Auqué et al. 2013; Capezzuoli et al. 2010; Das and Mohanti 2005; Irion and Müller 1968; Janssen et al. 1999; Manzo et al. 2012; Scholl and Taft 1964; Vazquez-Urbez et al. 2012).

Level 1.2

This unit consists of large calcitic-crystallitic and micritic calcite, along with cryptocrystalline aggregates with sizes from 400 µm to 7 mm in length (Fig. 3b and d). In PPL


LvL 2
LvL 3
a
1 cm
c
d
M.M.2.1
b
Al Si P Mg Mn Fe Ca
1 cm
c
1000 µm
d
500 µm
e
g
h
1 cm
M.M.2.2
f
Al Si P Fe Ca
1 cm
g
1000 µm
h
500 µm
i
k
l
1 cm
M.M.2.3
j
Al Si P Mg Fe Ca
1 cm
k
1000 µm
l
1000 µm

◂**Fig. 4** Stratigraphic sequence in the east profile of square L6. **a** Scan of thin section MM-2.1 White lines differentiate discrete episodes where charred organic matter was accumulated. Outside these layers, the sediments are anthropogenic, but with higher endokarstic sedimentary particles. **b** μ-XRF elemental mapping of block sample MM-2.1. **c** Photomicrograph in PPL. Abundant charred organic matter and a heated and trampled bone in the bottom of the micro-layer. **d** Photomicrograph in XPL. Contact between the two micro-layers (endokarstic with anthropogenic particles in the upper section and charred organic matter in the lower section. **e** Scan of thin section MM-2.2. White lines differentiate micro-layers which are rich in calcium carbonate. **f** μ-XRF elemental mapping of block sample MM-2.2. Green dashed lines delimitate events of high bone deposition (light blue). **g** Photomicrograph in XPL. Microlayer composed of endokarstic sediments. **h** Photomicrograph in XPL. Accumulation of calcium carbonate related to ashes (red arrows). **i** Scan of thin section MM-2.3. White lines differentiate a micro-layer rich in calcium and anthropogenic sediment particles. The lower dashed lines indicate the contact between Levels 2 and 3. **j** μ-XRF elemental mapping of block sample MM-2.3. The green dashed lines delimitate events of high bone deposition (light blue). Images (i) and (j) are mirrored. **k** Photomicrograph in PPL. Microlayer rich in charred anthropogenic materials and calcium, related to ashes. **l** Photomicrograph in XPL. The general groundmass of Level 3 with predominant endokarstic sediments

the sedimentary matrix has colors ranging from Pale yellowish to brownish, with inclusions of opaque grains. We observed coatings of continuous oriented clays, in addition to abundant coatings of iron oxide around the aggregates. According to González-Morales and Moure Romanillo (2008), during the excavation, this deposit was identified as a speleothem crust. Based on our micromorphological results, we interpret it as a rimstone dam (Clifford and Williams 2007; Goudie 2004). These dams correspond to depositional calcite barriers that form pools in caves, particularly in the channels of surface/underground streams or on flowstones. As suggested by Ford and Williams (2007), these are common in calcareous tufa and hot springs. These formations account for processes in which carbonate precipitation is very rapid, especially at the edges, given that the water films are usually thinner there. However, as in the calcareous tufa, some organics can be added during the depositional process. The Micro-XRF analysis showed that the aggregates are mainly composed of calcium, and phosphorus, as well as iron-rich clay minerals.

Inside the groundmass of the micritic aggregates, we identified a few rounded micritic aggregates with concentric laminations related to colonies of crystallized bacteria, as in Level 1.3 (Fig. 9d). However, as we found just a few of these tufa-related features, as well as a sedimentary matrix dominated by calcium carbonate aggregates with not too many detailed elements, we assume that this level represents a shift in the local environmental conditions within the cave. Similar observations of this feature were made by Simöes (2019) in Mesolithic shell middens in a karstic rockshelter in Asturias, associated with cementation processes of calcareous tufa.

The massive structure of the calcitic-crystallitic and cryptocrystalline aggregates, as well as the abundant illuvial clay coatings, suggests processes of phreatic cementation. Thus, the local environmental conditions of the cave during the formation of this layer did not allow the typical formation of the calcareous tufa, reflecting alternating periods of supersaturation of water, as well as a decrease of natural light within the cave.

Level 1.1

This unit displays a microstructure dominated by dense spheroidal micritic aggregates with simple packing voids. The coarse fraction (> 50 μm) is composed of frequent and well-sorted medium sand- to gravel-sized limestone fragments, and rare anorthic iron-oxide nodules fine sand-sized (Fig. 3a-b-c). The groundmass (< 50 μm) appears calcitic-crystallitic. It is made of needle-fiber calcite, quartz medium silt, and clays, which appear stratified and horizontally bedded in the bottom of the deposit (Fig. 3b-c). Most limestone fragments appear partly dissolved (with rounded and wavy edges), and exhibit fossils such as nummulites and bivalves, together with silt to fine sand of quartz. The quartz sand is a common coarse component of this unit, revealing that limestone dissolution was one of the main processes responsible for the formation of Level 1.1.

Discussion

Interpretation of units and site formation processes

A stratigraphic overview of site formation processes is presented on Fig. 10. Before diving into the interpretation and discussion of the features observed in Level 2, we provide a brief interpretation of Levels 1.1, 1.2, 1.3, and 3, which help us to reconstruct the non-anthropogenic sedimentation background at Fuente del Salín.

Geogenic sedimentation in Levels 1.1, 1.2, 1.3 and 3

Levels 3 and 1.1 originated from the dissolution and recrystallization of the carbonate rocks hosting the cave. Unlike Levels 1.1–1.3, in Level 3 we identified rare archaeological materials, such as fragments of bones and charcoals (Fig. 3l). These findings might reflect previously unknown visits to Fuente del Salín, predating the Gravettian occupation.

Water movement and weathering of the cave bedrock were responsible for the formation of the layers deposited after the Gravettian visits (Levels 1.1–1.3), which seem to have accumulated under wetter conditions. From bottom to

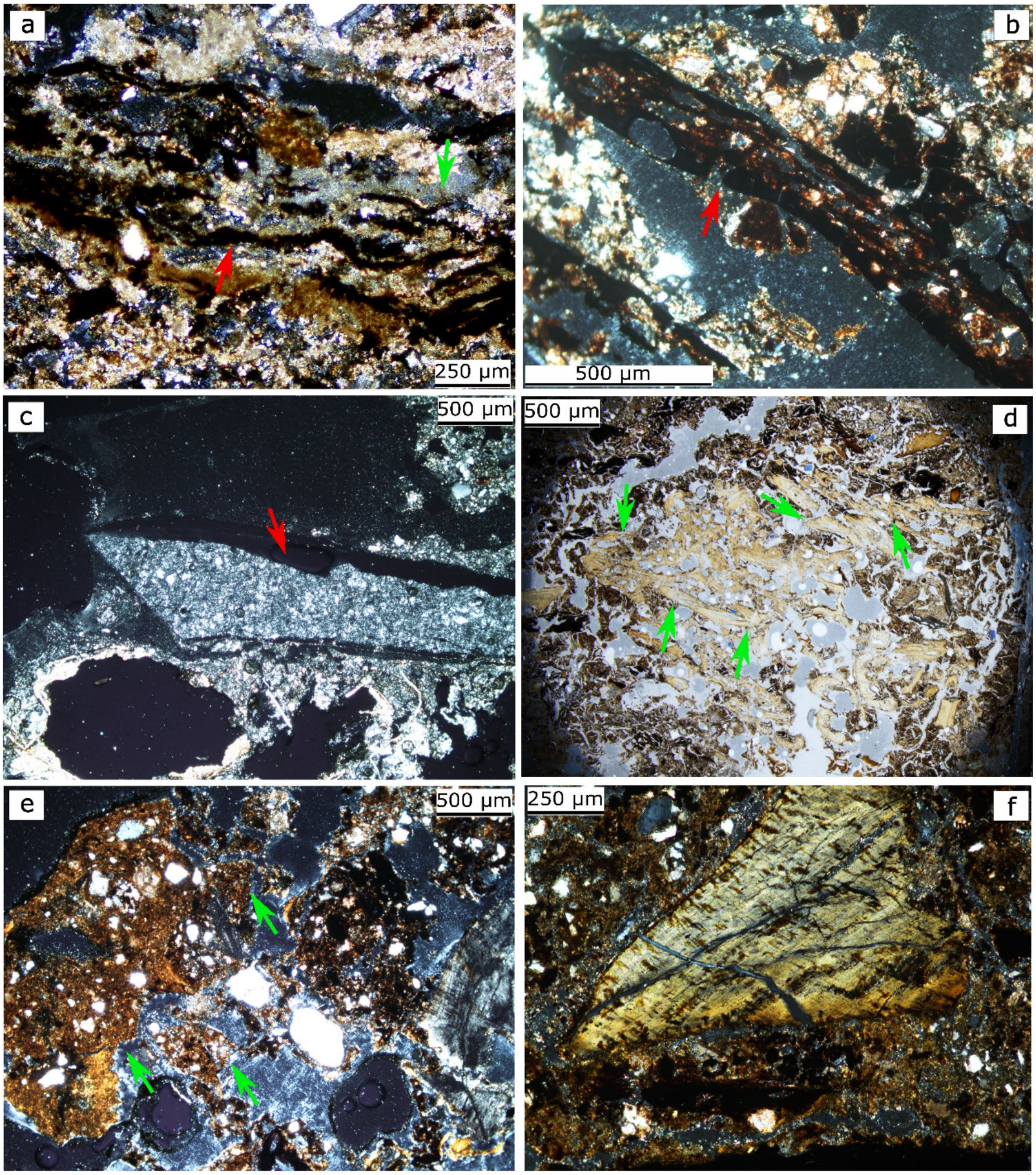


Fig. 5 Anthropogenic depositional processes. **a** Photomicrograph in XPL showing stringers (red arrow) alternating with ashy layers (green arrow). Stringers have been reported from Middle Stone Age deposits in South Africa, which are interpreted as grass beddings subsequently burned by foragers during sanitization activities (Binneman 2000; Goldberg et al. 2009; Miller and Sievers 2012; Sievers 2013; Sievers et al. 2022; Wadley et al. 2020, 2011; Walton 1951). **b** Photomicrograph in XPL-OIL displaying fat-derived char, derived from the heating of faunal remains (red arrow). **c** Photomicrograph in XPL exhibiting a knapped lithic artifact composed of cryptocrystalline chert (red arrow). **d** Photomicrograph in PPL from the upper central section of MM-2.3, showing a singular discard event of burned and fresh bones, most of them broken in situ (green arrows) capped by a layer of charred organic materials from Level 2. **e** Photomicrograph in XPL showing rubified clay aggregates in Level 2 (green arrows). **f** Photomicrograph in XPL depicting a heated bone exhibiting orange color and internal fractures due to the action of fire

top, Level 1.3 corresponds to a calcareous tufa formed by cyanobacteria, mosses, and algae (Fig. 9). These organisms require light, as well as wet and warm environments to live (Capezzuoli et al. 2014; Dabkowski 2014; Pentecost 1995, 2005a, b). We conclude that the ceiling collapse that marked the end of the Gravettian occupation at the site did not seal completely the entrance used by Paleolithic foragers but left the cave partly accessible. Level 1.2 consists of a rimstone dam (Fig. 3a-b-d). Our micromorphological findings contrast with field descriptions made by the excavators, which assigned this feature to Level 1.3 (Morales and Romanillo 2000; González-Morales and Moure Romanillo 2008). This type of speleothem commonly forms above tufa (Clifford and Williams 2007; Goudie 2004), and reflects a shift in the local environmental conditions, in which there was a supersaturation of water and a lack of light within the cave. In the upper part and across Level 1.2, we identified a lamellar accumulation of illuvial clays, including dusty clay capping, clay coatings, and clay intercalations (Figs. 3b-d; Online Resource 1d) (Mallol and Goldberg 2017; Stoops 2020). These clays came either from the weathering of the limestone bedrock or from the erosion of soils developed above the cave (Karkanas and Goldberg 2013) and deposited when a high amount of water drained through the porous rimstone dam (Level 1.2) (Gerasimova and Savitskaya 2020; Goldberg 2000, 2001; Inglis et al. 2018; Kourampas et al. 2009; Patania et al. 2019; Stephens et al. 2017).

Evidence of fire use and site maintenance in Level 2

Level 2 at Fuente del Salín resulted from three main anthropogenic activities: fire use, waste dumping, and site maintenance (Figs. 6 and 10). Although the high frequency of burnt bones (75%), charcoal, and fat-derived chars indicate intensive fire use by foragers, our thin section study revealed only a few in situ combustion features within this unit (Mallol et al. 2017; Mentzer 2014). In general, these combustion features are similar to intact combustion structures as defined by Mallol et al. (2017). These consist of up to 0.5 cm thick, stacked, microlaminated layers, exhibiting a sequence of endokarstic and anthropogenic sediment with some rubified clay aggregates (MF1), covered with articulated, recrystallized, and cemented ashes (MF2), carbonized comminuted organic matter (MF3) and microlayers with only endokarstic sediments (MF4) (Fig. 7). MF4 is associated with a brief period of abandonment of the cave by Gravettian foragers, as it lacks evidence of anthropogenic input. As the sampling strategy did not cover the whole sequence horizontally, this interpretation should be considered with caution.

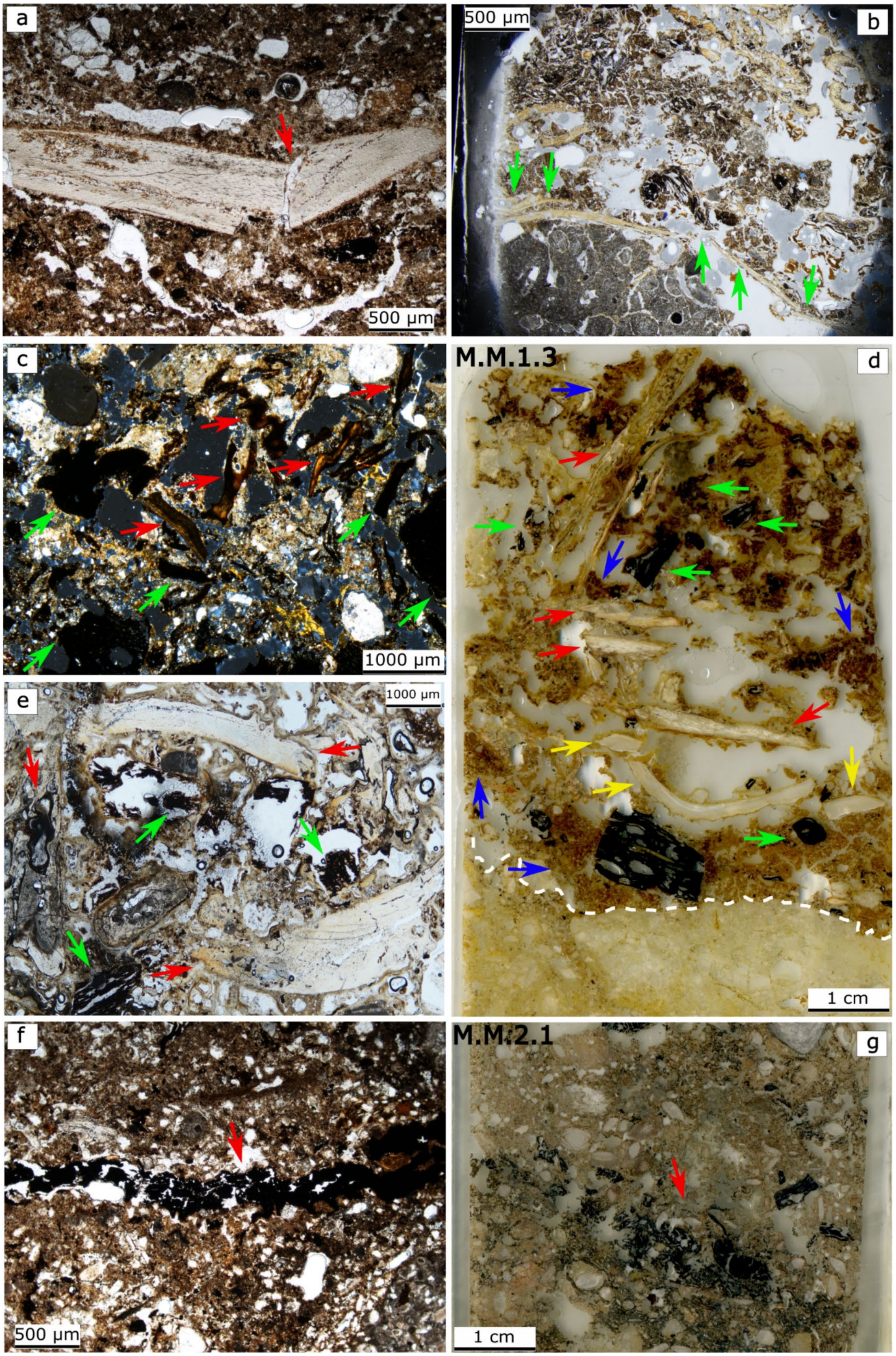
We did not identify reddened substrate as part of the combustion features, like the ones described by Mallol et al. (2017). Instead, we observed some rubified clay aggregates (Fig. 5e). This could be explained by several factors. First, the endokarstic sediment at Fuente del Salín cave is primarily composed of limestone sands, which, rather than reddening, undergo a chemical transformation from calcium carbonate to calcium hydroxide (Aldeias et al. 2016; Canti and Linford 2000; Toffolo and Boaretto 2014). Second, although iron is present in the sediments, related to geogenic, biogenic, and anthropogenic sources, it is possible that the fires at the site did not reach sufficiently high temperatures. Third, other factors, such as the moisture content and the low porosity of the endokarstic sediments, may have also played an important role (Karkanas 2021).

The features we identified at Fuente del Salín are probably related to simple open hearths, in which combustion is contained by the horizontal arrangement of the fuel, and even by the rock walls of the cave. These fireplaces might have been used for cooking, heating, and cleaning habitational surfaces (Mallol et al. 2017). We also identified “stringer-like” features (Homsey and Capo 2006; Karkanas and Goldberg 2010, 2020), which might correspond to grass beddings burned by foragers during sanitization activities (Fig. 5a) (Binneman 2000; Goldberg et al. 2009; Miller and Sievers 2012; Sievers 2013; Sievers et al. 2022; Wadley et al. 2020, 2011; Walton 1951).

Results of μ-XRF elemental analysis revealed that calcium (49%), manganese (11.4%), and iron (7.9%) are the elements more abundant within the combustion features of Level 2 (Figs. 7 and 8). Considerable amounts of manganese are not present in the bedrock hosting Fuente del Salín. Therefore, its occurrence in combustion features might be related to hunter-gatherer activity. Heyes et al. (2016) argued that Neanderthals foraged and used manganese dioxide to reduce the autoignition temperature of wood and increase the combustion rate of charcoal at Middle Paleolithic sites in France. Recent experiments by Sorensen (2024) confirm this model, showing that adding MnO_2 powder to tinder can make it nearly twice as effective as untreated tinder, enhancing its ability to capture and propagate sparks more efficiently. This technology could have significantly improved the ability of Paleolithic human groups to produce fire quickly and easily.

It is plausible that Gravettian foragers employed similar techniques to enhance fuel performance at Fuente del Salín. However, the presence of iron and manganese oxides in bone-rich layers has also been associated with bacterial activity, as bones provide nutrients for manganese-oxidizing bacteria (Shahack-Gross et al. 1997). Despite evidence that Neanderthals and Upper Paleolithic humans were proficient fire users, collected MnO_2-rich rocks, and even scraped these rocks to produce powder (Bodu et al. 2014; Pitarch Martí et al. 2019; Soressi et al. 2008), the hypothesis that the high concentrations of manganese oxides in Level 2 of Fuente del Salín are linked to human activity should be treated with caution.

Aside from combustion features, as a whole Level 2 exhibits micromorphological characteristics common in deposits accumulated by dumping and trampling (Fig. 6), such as heterogeneous microstructure, low compaction, high porosity, random orientation of the components, and co-occurrence of heated and unheated organic remains mixed with low amounts of endokarstic sediment (Figs. 3e-i, 4) (Grono et al. 2022, p. 14; Karkanas & Goldberg 2018, p. 107; Matthews et al. 1997).


a
500 µm
500 µm
b
c
1000 µm
M.M.1.3
d
e
1000 µm
1 cm
f
500 µm
M.M.2.1
g
1 cm

◂**Fig. 6** Trampling: **a** Photomicrograph in PPL showing a trampled bone (red arrow). **b** Photomicrograph in PPL depicting a trampled bone broken in situ in Level 2 (green arrows indicate the fractures). Dumping and raking-out: **c** Photomicrograph in XPL displaying the sedimentary matrix composed of heated bones (red arrows), charred organics (green arrows), and altered ashes with a chaotic arrangement and an open microstructure. **d** Scan of MM-1.3, depicting processes of raking-out. Fresh and heated bones (red arrows), charcoal (green arrows), shells (yellow arrows), and rubified clay aggregates (blue arrows) are unsorted, unoriented, and randomly distributed (Banerjea et al. 2015). **e** Photomicrograph in PPL displaying similar processes as shown in (c). Compacted combustion features: Photomicrograph (**f**) and scan of MM-2.1 (**g**) depict comprised and trampled microlayers of charred organics

We documented evidence of trampling through Level 2, with this anthropogenic process resulting in different micromorphological features. In the lower part of this unit, trampling compacted combustion features and fractured bones and shells, without displacing them (Fig. 4). We also documented trampling surfaces, as evidenced by multiple up to 2 cm thick layers made exclusively from heated and unheated, stacked, sub-horizontal animal bones (MM-2.2 and 2.3 in Fig. 4f-j), some of which appear broken in situ. Contrarily, in the upper part of Level 2, trampling and other post-depositional processes caused the displacement of fire residues (Fig. 3e-i). Such higher post-depositional disturbance appears more evident in the west profile of square K6. Site maintenance activities, such as raking-out (Matthews 2005; Shillito and Matthews 2013) or sweeping (Fondrillon 2007; Macphail 1994; Miller et al. 2010) were possibly more intensive in this part of the site (Fig. 6), because this cave area is slightly more spacious. Level 2 in this profile was also more intensively disturbed by bioturbation (Figs. 3e-i, Online Resource 1a) and secondary carbonate formation, due to intensive biological activity and water dropping near the original entrance to the cave. High bioturbation in Level 2 was probably also due to its high organic content, which attracted soil fauna and insects that feed on organic remains (Mallol et al. 2017; Schilt et al. 2017).

In the upper part of Level 2 most of the bones present hypo-, quasi-, and coatings of micrite (some laminated) and microsparite, along with calcite crystals in the shape of needle fibers (Figs. 3k, Online Resource 1c-f). These processes were probably associated with the dissolution and recrystallization of the limestone bedrock and the archaeological shells and ashes (Durand et al. 2010; Villagran and Poch 2014).

In the central part of Level 2, we identified a discrete (1 cm thick) layer composed of endokarstic sediment (MF4) (Fig. 4e-f-g). This is probably related to a phase of cave abandonment by Gravettian foragers. Further precision dating using alternative methods like archaeomagnetism (Herrejón-Lagunilla et al. 2024) might help to establish the duration of this phase and correlate it with local and regional environmental fluctuations.

In summary, Level 2 was mostly accumulated by Gravettian hunter-gatherers during intensive fire use alternating with phases of ground surface clearing and site maintenance (Aldeias and Bicho 2016; Goldberg et al. 2009; Miller et al. 2010; Miller and Sievers 2012).

Gravettian pyrotechnology: a cultural trait

The comparison of data presented in this paper and previous studies shows that at Fuente del Salín, Gravettian foragers lit fires to perform different tasks. High frequency of burnt fish bones heated at temperatures between 525°C and 645°C (Blanco-Lapaz et al. 2023; González-Echegaray 2020; Villagran et al. 2017a) show that fires were primarily used for cooking. However, we cannot exclude the possibility of accidental heating of some of the bones. The “stringer-like” features we identified in thin sections (Figs. 5a and 7g) might reflect sanitization practices to clear living surfaces of waste and pests (Binneman 2000; Goldberg et al. 2009; Miller and Sievers 2012; Sievers 2013; Sievers et al. 2022; Wadley et al. 2020, 2011; Walton 1951). The high concentration of manganese oxides in μ-XRF spectra suggests that Gravettian foragers might have used this element to improve fuel performance at Fuente del Salín. The recurrent presence of stacked combustion features (Fig. 7c) alternating with phases of raking and dumping (Figs. 3e-i, 4k and 6) indicates that Gravettian hunter-gatherers frequently reused fireplaces. The time interval between each hearth use was probably short, considering that Level 2 accumulated in a fraction of the 3 ky cal BP period of the calibration range (Blanco-Lapaz et al. 2023; González-Morales and Moure Romanillo 2008).

Comparable observations concerning the intensity and use of fire were previously reported from Gravettian sites located in central and eastern Europe (Ajas et al. 2013; Allsworth-Jones et al. 2018; Anghelinu et al. 2018; Goldberg et al. 2003; Haită, 2018; Miller 2015; Murphree and Aldeias 2022; Schiegl et al. 2003; Schilt et al. 2017; Vandiver et al. 1989; Villaverde et al. 2021) as well as a few sites in Iberia (Villaverde et al. 2021). Our results from Fuente del Salín further illustrate that these activities were carried out across different climates and environments. We conclude that these fire-use traits can be regarded as truly cultural and are likely connected with other lifeway aspects of Gravettian hunter-gatherers (Murphree and Aldeias 2022).

Paleodemographic studies revealed that, similarly to the Aurignacian, Gravettian foragers had low population density (4.3 to 0.3 forager/km^2) (Bicho et al. 2017; Bocquet-Appel et al. 2005; Maier 2017; Schmidt and Zimmermann 2019). Despite moving within regions up to 900 km wide, these populations had somewhat restricted

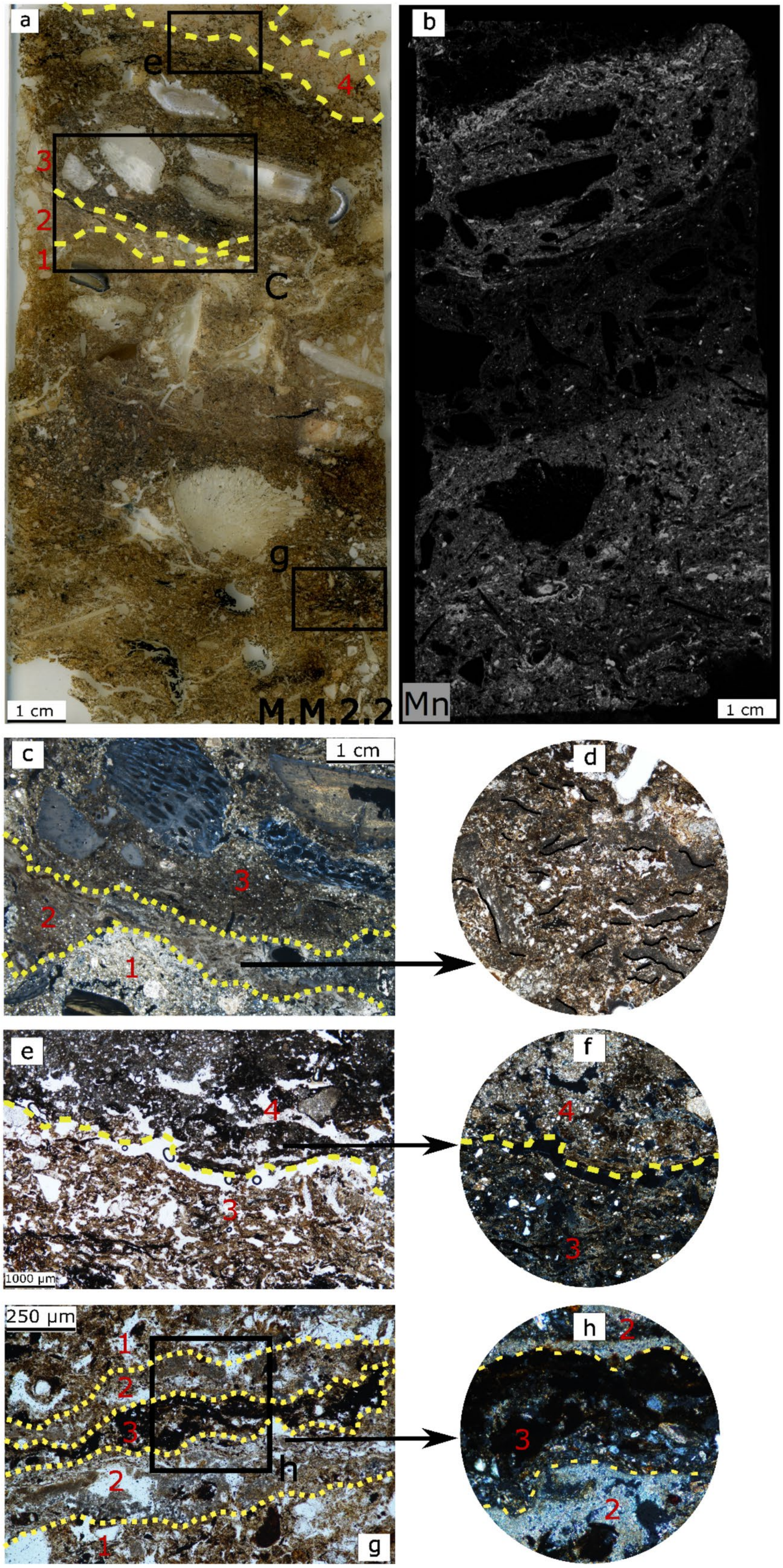


Fig. 7 Combustion features. **a** Scan of the thin section MM-2.2. Yellow dashed lines point to MFs. **b** µ-XRF elemental mapping of the block sample corresponding to MM-2.2 showing high amounts of Magnesium concentrated in the upper and lower sections. See Fig. 8. **c** Photomicrograph in XPL depicting microlaminated combustion layers composed of Endokarstic sediments with anthropogenic input (**MF1**), articulated ashes (**MF2**), burnt residues including bones, shells, ashes, charcoal, and fat-derived char (**MF3**). **d** Photomicrograph in PPL showing horizontal articulated ashes (black lines) (Mentzer 2014) including some calcined tissues. **e–f** Photomicrographs in PPL and XPL depicting the limit between **MF3** and **MF4** (endokarstic sediments without anthropogenic particles). **g** Photomicrograph in PPL displaying a charred organic matter layer (**3**) sandwiched between ashes layers (**2**) and endokarstic sediments (**1**). **h** Same as (**f**) but in XPL

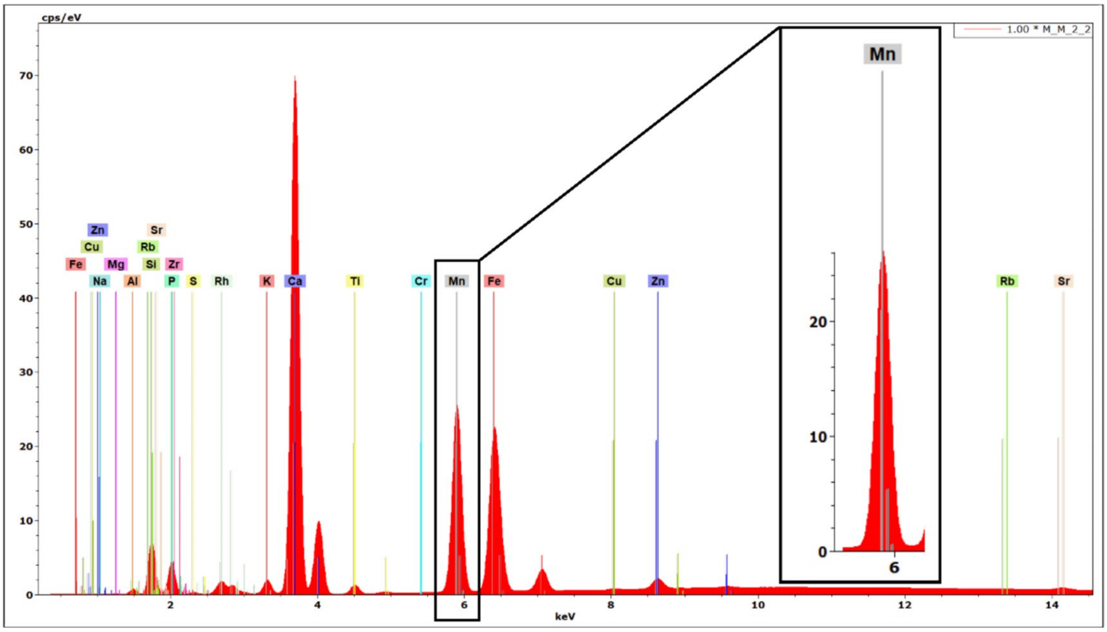


Fig. 8 Spectrum of the µ-XRF elemental mapping of the block sample MM-2.2, from Level 2. Note the high concentration of Calcium (49%), Iron (7.9%), and Manganese (11.4%)

social networks until 27 ka cal BP, as evidenced by their limited gene flow and distinct mortuary practices (Posth et al. 2023). The combined high levels of mobility and multi-seasonal sedentism of Gravettian groups throughout Europe are further supported by data from human bones, lithic technology, raw materials, and botanical remains (Aranguren et al. 2015; Bradtmöller et al. 2016; Holt 2003; Kozłowski 2015; Marreiros and Bicho 2013; Moreau 2009; Moreau et al. 2016; Scheer 1993; Taller et al. 2019; Trinkaus 2005; Vignoles et al. 2021). We conclude that intensive burning, intensive reuse of combustion features, and sanitization practices as observed at several Gravettian sites throughout Europe, including Fuente del Salín, likely reflect the settlement pattern of these foragers.

These fire use practices align with known behaviors and settlement dynamics that characterize most Gravettian sites in Central Europe and Iberia, where semi-sedentary practices (Simonet 2017) can be linked to more intensive fire use. As Gravettian foragers became less mobile, they inhabited specific sites more frequently and for extended periods. This reduced mobility allowed them more time to gather and store wood with less effort, resulting in the more intensive accumulation of fire residues at fewer sites. This triggered an increased need for site maintenance, with Gravettians likely managing waste not only through raking but also by using controlled burns to eliminate pests.

Conclusions

In this study, we reconstructed the formation processes of the archaeological sequence accumulated at Fuente del Salín and discussed its implications for the study of Gravettian fire use.

The earlier, potential evidence of forager visits to Fuente del Salín comes from the lowermost Level 3, where we documented rare bones and charcoals (Figs. 3i-l and 10). Due to the lack of stone tools and absolute dates from this layer, we are unable to verify whether these remains were deposited by pre-Gravettian foragers. Between 29 and 26 ky cal BP, Gravettian hunter-gatherers occupied intensively Fuente del Salín, as seen in Level 2. This change in site use coincided with a shift towards a drier climate, probably reflecting regional environments (Fernández-García et al. 2023). Our micromorphological and µ-XRF results revealed that Level 2 was accumulated during two distinct occupations, separated by a brief phase of abandonment (Figs. 4e-g). Further research is necessary to investigate the cause of this discontinuity in the forager presence at the site. Within Level 2, we identified two main types of potential combustion features in situ. The most frequent consists of stacked MFs of articulated and recrystallized woody ashes, heated soil aggregates, and burnt residues, which we interpreted as likely remnants of stacked open hearths (Figs. 6 and 7) (Mallol et al. 2017).

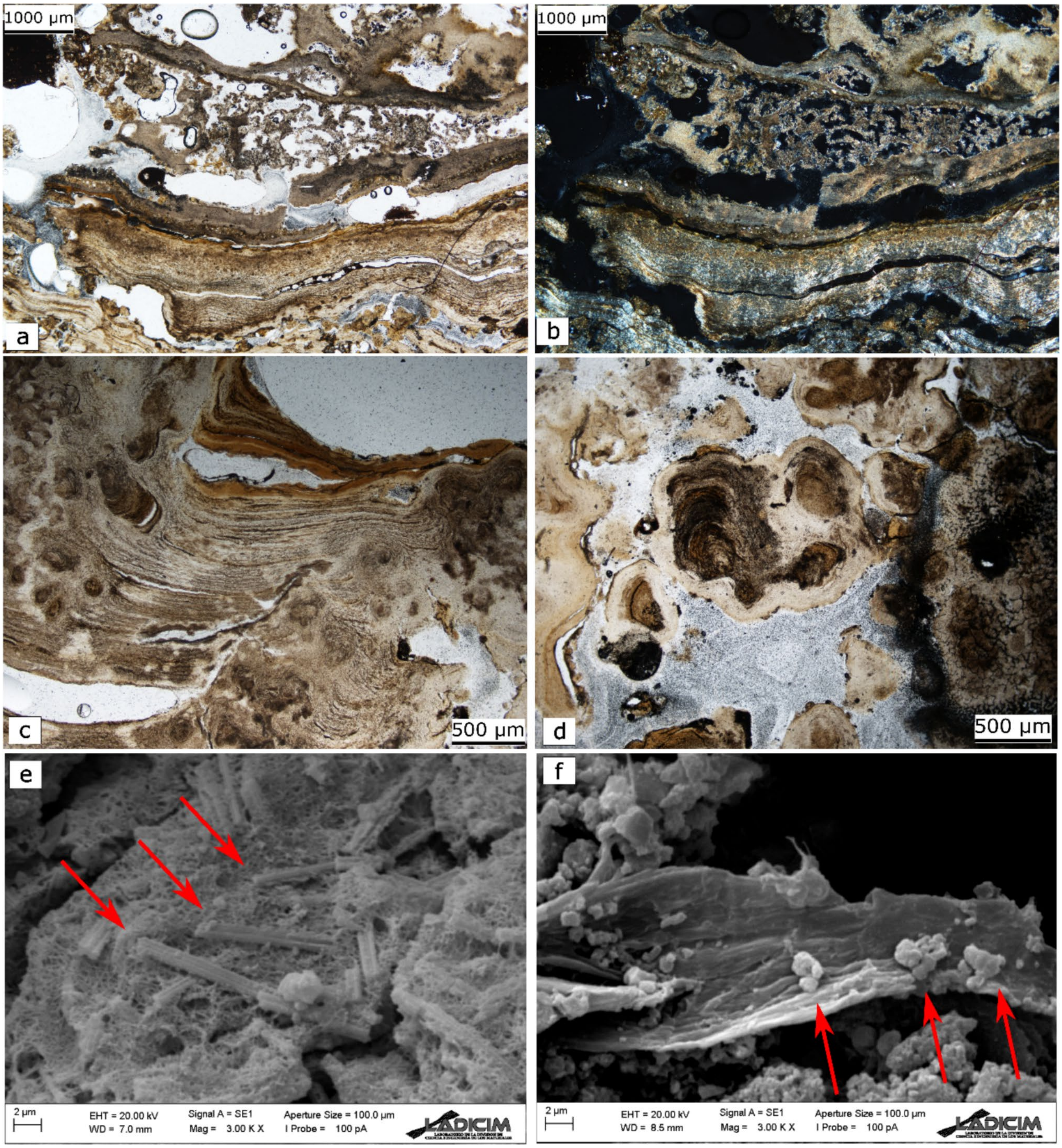


Fig. 9 Calcareous tufa from Level 1.3. **a** Photomicrograph in PPL displaying lamellar micritic, at the bottom, and sparitic spongy microstructure, above. Note the infiltration of iron oxides and organic matter in the horizontal plane voids. **b** Same as (a) but in XPL. **c-d** Photomicrographs in PPL showing rounded micritic aggregates with concentric laminations related to colonies of crystallized bacteria (Simões 2019). **e–f** SEM photomicrographs. **e** Needle fiber calcite crystals from the tufa deposit (red arrows) at 3.00 K X magnification (Das and Mohanti 2005; Janssen et al. 1999; Manzo et al. 2012). **f** Moss leaf with attached calcite crystals (red arrows) at 3.00 K X magnification (Auqué et al. 2013; Vazquez-Urbez et al. 2012)

Moreover, we documented "stringer-like" structures, comparable to the charred grass bedding documented in Middle Stone Age sites of South Africa (Figs. 5a and 7).

Features and components resulting from trampling, raking-out/sweeping, and dumping of fire residues are very common throughout Level 2 (see MM-1.2 in Figs. 3e-l–h

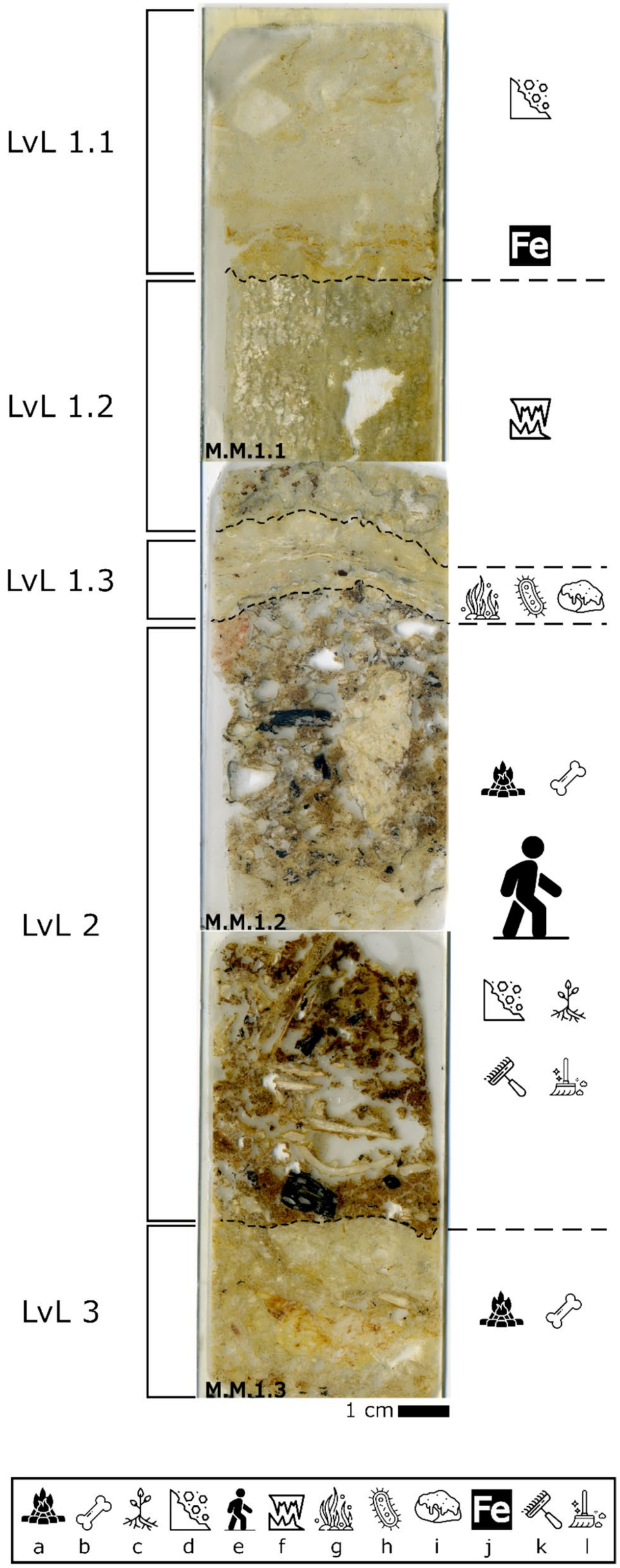


Fig. 10 Scheme of thin sections covering all stratigraphic levels with the association of biogenic, anthropogenic, and geogenic features. **a** Charcoal. **b** Bones. **c** Bioturbation. **d** Roof spall. **e** Trampling. **f** Stalagmitic crust. **g** Algae. **h** Bacteria. **i** Moss. **j** Fe accumulation. **k** Rake out. **l** Sweeping

and 6, Online Resource 1a-b). Furthermore, our study suggests that at Fuente del Salín the use of fire might have been correlated with the use of Manganese to improve fuel performance. However, this interpretation should be taken with care and deserves more studies to improve the comprehension of the pyrotechnology of the Gravettian foragers in northern Iberia. After 26 ky cal BP, a shift towards higher amounts of karstic water (Level 1) and a ceiling collapse probably discouraged hunter-gatherer stays at this site, which remained abandoned, favoring the preservation of its Gravettian record.

Intensity and mode of fire use as seen at Fuente del Salín are comparable with multiple Gravettian sites located east of the Pyrenees, as well as a few sites previously known from Iberia (Villaverde et al. 2021). In central and eastern Europe, in sites like Pavlov I, Dolní Věstonice I-II Czech Republic), Grub-Kranawetburg (Austria) and Abri Pataud (France), have been reported open flat hearths with evidence of stacking of several combustion features, such as charcoal-rich lenses, some of them separated by thin layers of loess, indicating different phases of repeated use and abandonment in the same heating location (Beresford-Jones et al. 2011; Bosch et al. 2011; Svoboda 2013). At Krems-Wachtberg (Austria) and Kostenki (Russia), hearths were described with multiple phases of combustion, and several lenses overlapped burned materials (Simon et al. 2014), reflecting the high intensity of fire use. Different features were observed at both Hohles Fels and Geißenklösterle (Germany), where no clear evidence of in situ combustion was found. Nevertheless, combustion features like charcoal, burned bones, ashes, and heated limestone, suggest dumping and other site maintenance activities (Miller 2015; Schiegl et al. 2003). In Iberia, the Spanish site of Cova de les Malledetes has evidence of an increase in the thickness and diameter of hearths between the Aurignacian and Gravettian periods (Villaverde et al. 2021), as a result not only of a longer occupation of the site, compared to the Aurignacian, but also an intensification of the fire use during the Gravettian.

The fact that Gravettian sites across Europe exhibit comparable fire use and technologies, despite differences in regional climates, seem to support the conclusion that these behavioral traits are equally important constituents of the Gravettian tradition. We argue that further studies on pyrotechnology at archaeological sites in non-periglacial regions will help to reinforce this conclusion.

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Author contributions G.A.C: Conceptualization; Formal analysis; Investigation; Methodology; Visualization; Writing—original draft. M.A.S.C: Conceptualization; Funding acquisition; Project administration; Supervision; Validation; Resources; Writing—original draft. A. B: Conceptualization; Formal analysis; Supervision, Writing—original draft. M. R. G.M: Conceptualization; Writing—review and editing; Resources; Validation; Project administration.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

Ajas A, Bertran P, Lemée L, Queffelec A (2013) Stratigraphy and Palaeopedology of the Palaeolithic Cave Site of Combe-Saunière, Southwest France. Geoarchaeology 28(5):432–449. https://doi.org/10.1002/gea.21451

Ajuaba S, Arenas C, Capezzuoli E (2021) Sedimentología de las tobas palustres pleistocenas y depósitos asociados del Valle del Ebrón (Cordillera Ibérica, España). Estudios Geológicos 77(1):e137. https://doi.org/10.3989/egeol.44131.593

Aldeias V, Bicho N (2016) Embedded behavior: human activities and the construction of the Mesolithic Shellmound of Cabeço da Amoreira, Muge, Portugal. Geoarchaeology 31(6):530–549. https://doi.org/10.1002/gea.21573

Aldeias V, Dibble HL, Sandgathe D, Goldberg P, McPherron SJP (2016) How heat alters underlying deposits and implications for archaeological fire features: a controlled experiment. J Archaeol Sci 67:64–79. https://doi.org/10.1016/j.jas.2016.01.016

Allsworth-Jones P, Borziac IA, Chetraru NA, French CAI, Medyanik SI (2018) Brînzeni: a multidisciplinary study of an Upper Palaeolithic site in Moldova. Proc Prehist Soc 84:41–76. https://doi.org/10.1017/ppr.2018.3

Alonso Gutiérrez S (2018) Análisis y caracterización de los pigmentos de la cueva de la Fuente del Salín (Muñorrodero, Cantabria): una aproximación desde la arqueología experimental Universidad de Cantabria]. http://hdl.handle.net/10902/14897

Altuna J, Mariezkurrena K, Peña P, Rios-Garaizar J (2013) Los niveles gravetienses de la cueva de Aitzbitarte III (Gipuzkoa). Industrias y faunas asociadas. Museo Nacional y Centro de Investigación de Altamira, monografías 23:184-204

Angelucci DE, Anesin D, Susini D, Villaverde V, Zapata J, Zilhão J (2018) A tale of two gorges: Late Quaternary site formation and surface dynamics in the Mula basin (Murcia, Spain). Quatern Int 485:4–22. https://doi.org/10.1016/j.quaint.2017.04.006

Anghelinu M, Niţă L, Murătoreanu G (2018) Le Gravettien et l'Épigravettien de l'Est de la Roumanie : une réévaluation. Anthropologie 122(2):183–219. https://doi.org/10.1016/j.anthro.2018.03.002

Aranguren B, Cavulli F, D'Orazio M, Grimaldi S, Longo L, Revedin A, Santaniello F (2015) Territorial exploitation in the Tyrrhenian Gravettian Italy: The case-study of Bilancino (Tuscany). Quatern Int 359–360:442–451. https://doi.org/10.1016/j.quaint.2014.07.009

Aubry T (1998) Olga Grande 4: uma sequência do Paleolítico superior no planalto entre o Rio Côa e a Ribeira de Aguiar. Rev Port Arqueol 1(1):1–22

Auqué L, Arenas C, Osácar MC, Pardo G, Sancho C, Vázquez-Urbez M (2013) Tufa sedimentation in changing hydrological conditions: the River Mesa (Spain). Geol Acta 11:85–102. https://doi.org/10.1344/105.000001774

Badal E, Martínez Varea CM, Cantó A, Angelucci DE, Villaverde Bonilla V, Zapata Crespo J, Zilhão J (2019) Firewood in the fireplace: fuel use in the solutrean of La Boja Rock-Shelter (Murcia, Spain). In Human adaptations to the Last Glacial Maximum: the Solutrean and its Neighbors. Cambridge Scholars Publishing, pp 337–352

Banerjea RY, Bell M, Matthews W, Brown A (2015) Applications of micromorphology to understanding activity areas and site formation processes in experimental hut floors. Archaeol Anthropol Sci 7(1):89–112. https://doi.org/10.1007/s12520-013-0160-5

Barbieri A, Bachofer F, Schmaltz EM, Leven C, Conard NJ, Miller CE (2021) Interpreting gaps: a geoarchaeological point of view on the Gravettian record of Ach and Lone valleys (Swabian Jura, SW Germany). J Archaeol Sci 127:105335. https://doi.org/10.1016/j.jas.2021.105335

Bentsen SE (2014) Using pyrotechnology: fire-related features and activities with a focus on the African Middle Stone Age. J Archaeol Res 22(2):141–175. https://doi.org/10.1007/s10814-013-9069-x

Bentsen SE, Wurz S (2019) A Song of Space and Fire Is There a Pyrotechnical Architecture of the African Middle Stone Age? In: D Gheorghiu (Ed.), Architectures of Fire: Processes, Space and Agency in Pyrotechnologies (pp. 1–15). Archaeopress. https://doi.org/10.2307/j.ctv1zcm08z.5

Beresford-Jones D, Taylor S, Paine C, Pryor A, Svoboda J, Jones M (2011) Rapid climate change in the Upper Palaeolithic: the record of charcoal conifer rings from the Gravettian site of Dolní Věstonice, Czech Republic. Quat Sci Rev 30(15):1948–1964. https://doi.org/10.1016/j.quascirev.2011.04.021

Berna F, Goldberg P (2007) Assessing Paleolithic pyrotechnology and associated hominin behavior in Israel. Israel J Earth Sci 56:107–121. https://doi.org/10.1560/IJES.56.2-4.107

Berna F, Goldberg P, Horwitz LK, Brink J, Holt S, Bamford M, Chazan M (2012) Microstratigraphic evidence of in situ fire in the Acheulean strata of Wonderwerk Cave, Northern Cape province, South Africa. Proc Natl Acad Sci 109(20):E1215–E1220. https://doi.org/10.1073/pnas.1117620109

Bicho N, Cascalheira J, Gonçalves C (2017) Early Upper Paleolithic colonization across Europe: Time and mode of the Gravettian diffusion. PLoS One 12(5):e0178506. https://doi.org/10.1371/journal.pone.0178506

Binneman JNF (2000) Results from two test excavations in the Baviaanskloof Mountains, Eastern Cape Province. South Afr Field Archaeol 9(1):81–92

Blanco-Lapaz A, Marín-Arroyo AB, Gutiérrez-Zugasti I, González-Echegaray de Yarto F, González-Morales MR (2023) Coastal and Inland subsistence strategies during the Gravettian in the Cantabrian Region (Northern Iberian Peninsula). Quat Sci Adv 12:100106. https://doi.org/10.1016/j.qsa.2023.100106

Bocquet-Appel J-P, Demars P-Y, Noiret L, Dobrowsky D (2005) Estimates of Upper Palaeolithic meta-population size in Europe from archaeological data. J Archaeol Sci 32(11):1656–1668. https://doi.org/10.1016/j.jas.2005.05.006

Bodu P, Salomon H, Leroyer M, Naton H-G, Lacarriere J, Dessoles M (2014) An open-air site from the recent Middle Palaeolithic in the Paris Basin (France): Les Bossats at Ormesson (Seine-et-Marne). Quatern Int 331:39–59. https://doi.org/10.1016/j.quaint.2013.10.029

Bosch M, Nigst P, Fladerer F, Antl-Weiser W (2011) Humans, bones and fire: Zooarchaeological, taphonomic, and spatial analyses of a Gravettian mammoth bone accumulation at Grub-Kranawetberg (Austria). Quat Int 252. https://doi.org/10.1016/j.quaint.2011.08.019

Bösken J, Sümegi P, Zeeden C, Klasen N, Gulyás S, Lehmkuhl F (2018) Investigating the last glacial Gravettian site 'Ságvár Lyukas Hill' (Hungary) and its paleoenvironmental and geochronological context using a multi-proxy approach. Palaeogeogr Palaeoclimatol Palaeoecol 509:77–90. https://doi.org/10.1016/j.palaeo.2017.08.010

Bradtmöller M, Marreiros J, Pereira T, Bicho N (2016) Lithic technological adaptation within the Gravettian of the Iberian Atlantic region: Results from two case studies. Quatern Int 406:3–24. https://doi.org/10.1016/j.quaint.2015.08.075

Bradtmöller M (2015) The Gravettian occupation of Level 4 Cueva Morín and it´s regional context La ocupación Gravetiense Nivel 4 de Cueva Morín y el contexto regional. Munibe Antropologia-Arkeologia

Brönnimann D, Portmann C, Pichler SL, Booth TJ, Röder B, Vach W, … Rentzel P (2018) Contextualising the dead – Combining geoarchaeology and osteo-anthropology in a new multi-focus approach in bone histotaphonomy. J Archaeol Sci 98:45-58. https://doi.org/10.1016/j.jas.2018.08.005

Brugal J-P (2006) Petit gibier et fonction de sites au Paléolithique supérieur. Les ensembles fauniques de la grotte d'Anecrial (Porto de Mos, Estremadure, Portugal). Paléo 18. https://doi.org/10.4000/paleo.140

Calvo A, Tapia J, Arrizabalaga A, Iriarte-Chiapusso M-J (2011) El yacimiento de Ametzagaina (Donostia, País Vasco). Un campamento gravetiense al aire libre en el Cantábrico [The archaeological site of Ametzagaina (Donostia, Basque Country). A gravettian open air campsite in the Cantabrian region]. https://doi.org/10.13140/2.1.3964.7521

Canora C, Cuevas Rodríguez J, Martínez Díaz JJ, Garralón A (2023) Analysis of a travertine system controlled by the transpressional activity of the Alhama de Murcia fault: The Carraclaca site, eastern Betic Cordillera, Spain [Original Research]. Front Earth Sci 11. https://doi.org/10.3389/feart.2023.1060363

Canti M (2003) Aspects of chemical and microscopic characteristics of plant ashes found in archaeological soils. CATENA 54:339–361. https://doi.org/10.1016/S0341-8162(03)00127-9

Canti MG, Linford N (2000) The effects of fire on archaeological soils and sediments: temperature and colour relationships [Article]. Proc Prehist Soc 66:385–395

Capezzuoli E, Gandin A, Sandrelli F (2010) Calcareous tufa as indicators of climatic variability: a case study from southern Tuscany (Italy). Geol Soc Lond Spec Publ 336(1):263–281. https://doi.org/10.1144/SP336.14

Capezzuoli E, Gandin A, Pedley M (2014) Decoding tufa and travertine (fresh water carbonates) in the sedimentary record: The state of the art. Sedimentology 61(1):1–21. https://doi.org/10.1111/sed.12075

Chafetz HS, Folk RL (1984) Travertines; depositional morphology and the bacterially constructed constituents. J Sediment Res 54(1):289–316. https://doi.org/10.1306/212f8404-2b24-11d7-8648000102c1865d

Clifford F, Williams P (2007) Karst Hydrogeology & Geomorphology. John Wiley & Sons Ltd. https://doi.org/10.1002/9781118684986

Cuenca-Solana D, Gutiérrez-Zugasti FI, González-Morales MR, … Clemente-Conte I (2013) Shell technology, rock art, and the role of marine resources during the Upper Paleolithic. Curr Anthropol 54(3):370-380. https://doi.org/10.1086/670325

Dabkowski J (2014) High potential of calcareous tufas for integrative multidisciplinary studies and prospects for archaeology in Europe. J Archaeol Sci 52:72–83. https://doi.org/10.1016/j.jas.2014.07.013

Das S, Mohanti M (2005) Sedimentology of holocene tufa carbonates in Orissa State, India. Carbonates Evaporites 20(1):8–33. https://doi.org/10.1007/BF03175445

Durand N, Monger HC, Canti MG (2010) 9 - Calcium Carbonate Features. In: Stoops G, Marcelino V, Mees F (eds) Interpretation of Micromorphological Features of Soils and Regoliths. Elsevier, pp 149–194. https://doi.org/10.1016/B978-0-444-53156-8.00009-X

Fernández-García M, Vidal-Cordasco M, Jones JR, Marín-Arroyo AB (2023) Reassessing palaeoenvironmental conditions during the Middle to Upper Palaeolithic transition in the Cantabrian region (Southwestern Europe). Quatern Sci Rev 301:107928. https://doi.org/10.1016/j.quascirev.2022.107928

Fernández-Navarro V, Camarós E, Garate D (2022) Visualizing childhood in Upper Palaeolithic societies: Experimental and archaeological approach to artists' age estimation through cave art hand stencils. J Archaeol Sci 140:105574. https://doi.org/10.1016/j.jas.2022.105574

Fernández-Palacios E, Jambrina-Enríquez M, Mentzer S, Vera C, Dinckal A, Égüez N, … Mallol C (2023) Reconstructing formation processes at the Canary Islands indigenous site of Belmaco

Cave (La Palma, Spain) through a multiproxy geoarchaeological approach. Geoarchaeology 38. https://doi.org/10.1002/gea.21972

Fondrillon M (2007) La formation du sol urbain: étude archéologique des terres noires à Tours (4e-12e siècle)

Ford D, Williams P (2007) Cave Interior Deposits. In Karst Hydrogeology and Geomorphology (pp. 271–320). https://doi.org/10.1002/9781118684986.ch8

Fullola J-M, Mangado X, Tejero J-M, Petit M-À, Bergadà M-M, Nadal J, … Mercadal O (2012) The Magdalenian in Catalonia (Northeast Iberia). Quat Int 272-273:55-74. https://doi.org/10.1016/j.quaint.2012.02.051

Gaspar R, Ferreira J, Carrondo J, Silva MJ, García-Vadillo FJ (2016) Open-air Gravettian lithic assemblages from Northeast Portugal: The Foz do Medal site (Sabor valley). Quatern Int 406:44–64. https://doi.org/10.1016/j.quaint.2015.12.054

Gerasimova MI, Savitskaya NV (2020) Micromorphological interpretation of natural and anthropogenic evolution of soils in Bykovo lacustrine-alluvial section of the Moskva River floodplain. Eurasian Soil Sci 53(7):950–959. https://doi.org/10.1134/S1064229320070030

Goldberg P (2000) Micromorphology and site formation at Die Kelders Cave I, South Africa. J Hum Evol 38(1):43–90. https://doi.org/10.1006/jhev.1999.0350

Goldberg P, Schiegl S, Meligne K, Dayton C, Conard NJ (2003) Micromorphology and site formation at Hohle Fels Cave, Schwabian Jura, Germany. E&G Quat Sci J 53(1):1–25. https://doi.org/10.3285/eg.53.1.01

Goldberg P, Miller CE, Schiegl S, Ligouis B, Berna F, Conard NJ, Wadley L (2009) Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. Archaeol Anthropol Sci 1(2):95–122. https://doi.org/10.1007/s12520-009-0008-1

Goldberg P, Macphail R (2006) Practical and Theoretical Geoarchaeology. https://doi.org/10.1002/9781118688182

Goldberg P, Holliday V, Ferring C (2001) Earth Sciences and Archaeology. https://doi.org/10.1007/978-1-4615-1183-0

Goldberg P (2001) Some micromorphological aspects of prehistoric cave deposits. Cahiers d'Archéologie du CELAT 10:161–75

González-Echegaray FdY (2020) Estrategias de subsistencia de los grupos humanos gravetienses de la Fuente del Salín. Estudio arqueozoológico de los macromamíferos en el nivel 2. http://hdl.handle.net/10902/19948

González-Morales M, Moure Romanillo J (2008) Excavaciones y estudio de arte rupestre en la cueva de la Fuente del Salin (Muñorrodero, Val de San Vicente). Campaña de 2000. In Actuaciones Arqueológicas en Cantabria, 2000 - 2003 (pp. 79–82)

Goudie AS (2004) Encyclopedia of Geomorphology. Routledge

Grono E, Friesem DE, Lam TMD, Nguyen TT, Hamilton R, Bellwood P, … Denham T (2022) Microstratigraphy reveals cycles of occupation and abandonment at the mid Holocene coastal site of Thach Lac, northern-central Vietnam. Archaeol Res Asia 31:100396. https://doi.org/10.1016/j.ara.2022.100396

Gutiérrez-Zugasti I, Cuenca Solana D, González Morales M, García Moreno A (2012) El aprovechamiento de moluscos y otros recursos litorales durante el Gravetiense en la región cantábrica: análisis arqueomalacológico de la cueva de la Fuente del Salín (Muñorrodero, Cantabria). In Pensando el Gravetiense: nuevos datos para la región cantábrica en su contexto peninsular y pirenaico (pp. 416–428). Ministerio de Educación, Cultura y Deporte

Haită C (2018) The micromorphology of the Gravettian occupation sequence from Poiana Cireşului (Piatra Neamţ, Romania). Annales d'Université "Valahia" Târgovişte. Section d'Archéologie et d'Histoire, pp 7–16. https://doi.org/10.3406/valah.2018.1276

Herrejón-Lagunilla Á, Villalaín JJ, Pavón-Carrasco FJ, Serrano Sánchez-Bravo M, Sossa-Ríos S, Mayor A, … Carrancho Á (2024) The time between Palaeolithic hearths. Nature. https://doi.org/10.1038/s41586-024-07467-0

Heyes PJ, Anastasakis K, de Jong W, van Hoesel A, Roebroeks W, Soressi M (2016) Selection and use of manganese dioxide by Neanderthals. Sci Rep 6(1):22159. https://doi.org/10.1038/srep22159

Hlubik S, Berna F, Feibel C, Braun D, Harris JWK (2017) Researching the nature of fire at 1.5 Mya on the site of FxJj20 AB, Koobi Fora, Kenya, using high-resolution spatial analysis and FTIR spectrometry. Curr Anthropol 58(S16):S243–S257. https://doi.org/10.1086/692530

Holt BM (2003) Mobility in Upper Paleolithic and Mesolithic Europe: Evidence from the lower limb. Am J Phys Anthropol 122(3):200–215. https://doi.org/10.1002/ajpa.10256

Homsey LK, Capo RC (2006) Integrating geochemistry and micromorphology to interpret feature use at Dust Cave, a Paleo-Indian through middle-archaic site in Northwest Alabama. Geoarchaeology 21(3):237–269. https://doi.org/10.1002/gea.20103

Inglis RH, French C, Farr L, Hunt CO, Jones SC, Reynolds T, Barker G (2018) Sediment micromorphology and site formation processes during the Middle to Later Stone Ages at the Haua Fteah Cave, Cyrenaica. Libya Geoarchaeology 33(3):328–348. https://doi.org/10.1002/gea.21660

Irion G, Müller G (1968, 1968) Mineralogy, Petrology and Chemical Composition of Some Calcareous Tufa from the Schwäbische Alb, Germany. Recent Developments in Carbonate Sedimentology in Central Europe, Berlin, Heidelberg

Janssen A, Swennen R, Podoor N, Keppens E (1999) Biological and diagenetic influence in Recent and fossil tufa deposits from Belgium. Sed Geol 126(1):75–95. https://doi.org/10.1016/S0037-0738(99)00033-0

Karkanas P (2021) All about wood ash: Long term fire experiments reveal unknown aspects of the formation and preservation of ash with critical implications on the emergence and use of fire in the past. J Archaeol Sci 135:105476. https://doi.org/10.1016/j.jas.2021.105476

Karkanas P, Goldberg P (2010) Site formation processes at Pinnacle Point Cave 13B (Mossel Bay, Western Cape Province, South Africa): resolving stratigraphic and depositional complexities with micromorphology. J Hum Evol 59(3):256–273. https://doi.org/10.1016/j.jhevol.2010.07.001

Karkanas P, Goldberg P (2013) 6.23 Micromorphology of Cave Sediments. In: Shroder JF (ed) Treatise on Geomorphology. Academic Press, pp 286–297. https://doi.org/10.1016/B978-0-12-374739-6.00120-2

Karkanas P, Goldberg P (2018) Reconstructing Archaeological Sites: Understanding the Geoarchaeological Matrix. John Wiley & Sons Ltd

Karkanas P, Goldberg P (2020) Soil Micromorphology. In: Gilbert AS, Goldberg P, Mandel RD, Aldeias V (eds) Encyclopedia of Geoarchaeology. Springer International Publishing, pp 1–13. https://doi.org/10.1007/978-3-030-44600-0_27-1

Kourampas N, Simpson IA, Perera N, Deraniyagala SU, Wijeyapala WH (2009) Rockshelter sedimentation in a dynamic tropical landscape: Late Pleistocene-Early Holocene archaeological deposits in Kitulgala Beli-lena, southwestern Sri Lanka. Geoarchaeology 24(6):677–714. https://doi.org/10.1002/gea.20287

Kozłowski JK (2015) The origin of the Gravettian. Quatern Int 359–360:3–18. https://doi.org/10.1016/j.quaint.2014.03.025

Lucena A, Martínez S, Angelucci D, Badal-García E, Villaverde V, Zapata J, Zilhão J (2012) La ocupación solutrense del Abrigo de la Boja (Mula, Murcia, España). Espacio, Tiempo y Forma. Serie I, Nueva época. Prehistoria y Arqueología 5:447-454. https://doi.org/10.5944/etfi.5.2012.8290

Macphail RI (1994) The reworking of urban stratigraphy by human and natural processes. In: Hall AR, Kenward HK (eds) Urban-rural connexions: perspectives from environmental archaeology.

Symposia of the Association for Environmental Archaeology No. 12. Oxbow Monograph, vol 47. Oxford, pp 13–43

Maier A (2017) Population and settlement dynamics from the Gravettian to the Magdalenian. Mitteilungen der Gesellschaft für Urgeschichte 26:83–101

Mallol C, Hernández CM, Cabanes D, Machado J, Sistiaga A, Pérez L, Galván B (2013) Human actions performed on simple combustion structures: An experimental approach to the study of Middle Palaeolithic fire. Quatern Int 315:3–15. https://doi.org/10.1016/j.quaint.2013.04.009

Mallol C, Goldberg P (2017) Cave and Rock Shelter Sediments. In Archaeological Soil and Sediment Micromorphology (pp. 359–381). https://doi.org/10.1002/9781118941065.ch34

Mallol C, Mentzer SM, Miller CE (2017) Combustion Features. In Archaeological Soil and Sediment Micromorphology (pp. 299–330). https://doi.org/10.1002/9781118941065.ch31

Manzo E, Perri E, Tucker ME (2012) Carbonate deposition in a fluvial tufa system: processes and products (Corvino Valley – southern Italy). Sedimentology 59(2):553–577. https://doi.org/10.1111/j.1365-3091.2011.01266.x

Marín-Arroyo AB, Geiling JM, Jones EL, Carvalho M, Morales MRG, Straus LG (2023) Seasonality of human occupations in El Mirón Cave: Late Upper Paleolithic hunter-gatherer settlement-subsistence systems in Cantabrian Spain. J Paleolithic Archaeol 6(1):7. https://doi.org/10.1007/s41982-022-00134-8

Marreiros J, Bicho N (2013) Lithic technology variability and human ecodynamics during the Early Gravettian of Southern Iberian Peninsula. Quatern Int 318:90–101. https://doi.org/10.1016/j.quaint.2013.05.008

Matthews W, French CAI, Lawrence T, Cutler DF, Jones MK (1997) Microstratigraphic traces of site formation processes and human activities. World Archaeol 29(2):281–308. https://doi.org/10.1080/00438243.1997.9980378

Matthews W (2005) Life-cycle and life-course of buildings. In: Hodder I (ed) Catalhoyuk Perspectives: Themes from the 1995–9 Seasons. McDonald Institute for Archaeological Research and British Institute of Archaeology at Ankara, Cambridge

Mentzer SM (2014) Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. J Archaeol Method Theory 21(3):616–668. https://doi.org/10.1007/s10816-012-9163-2

Mentzer SM (2017) Micro XRF. In Archaeological Soil and Sediment Micromorphology (pp. 431–440). https://doi.org/10.1002/9781118941065.ch41

Miller CE (2015) A tale of two Swabian caves. Geoarchaeological investigations at Hohle Fels and Geißenklösterle. Kerns Verlag

Miller CE, Sievers C (2012) An experimental micromorphological investigation of bedding construction in the Middle Stone Age of Sibudu, South Africa. J Archaeol Sci 39(10):3039–3051. https://doi.org/10.1016/j.jas.2012.02.007

Miller C, Conard N, Goldberg P, Berna F (2010) Dumping, sweeping and trampling: experimental micromorphological analysis of anthropogenically modified combustion features. Palethnologie 2:25–37. https://doi.org/10.4000/palethnologie.8197

Morales MRG, Romanillo JAM (2000) Excavaciones y documentación del arte rupestre de la cueva de la Fuente del Salín: Muñorrodero, Val de San Vicente. In Actuaciones arqueológicas en Cantabria: 1984-1999. Consejería de Cultura, Turismo y Deporte, pp 149–150

Moreau L, Brandl M, Nigst PR (2016) Did prehistoric foragers behave in an economically irrational manner? Raw material availability and technological organisation at the early Gravettian site of Willendorf II (Austria). Quatern Int 406:84–94. https://doi.org/10.1016/j.quaint.2015.11.123

Moreau L (2009) Das Siedlungsmuster im Achtal zur Zeit des älteren Gravettien: zum Beitrag einer neuen Steinartefaktzusammensetzung Zwischen der Brillenhöhle und dem Geissenklösterle (schwäbische Alb, Alb-Donau-Kr.). Archäologisches Korrespondenzblatt 39(1):1–20

Moure Romanillo A, Gonzalez Morales M, González Sainz C (1985) Las pinturas paleolíticas de la cueva de La Fuente del Salín (Muñorrodero, Cantabria). Ars Praehistorica 13–23

Murphree WC, Aldeias V (2022) The evolution of pyrotechnology in the Upper Palaeolithic of Europe. Archaeol Anthropol Sci 14(10):202. https://doi.org/10.1007/s12520-022-01660-w

Musil R (2010) Palaeoenvironment at Gravettian Sites in Central Europe with emphasis on Moravia (Czech Republic): Die Paläoumwelt mitteleuropäischer Gravettien-Fundstellen mit Schwerpunkt auf Mähren (Tschechische Republik). Quartär-Internationales Jahrbuch Zur Erforschung Des Eiszeitalters und der Steinzeit 57:95–123

Nicholson RA (1992) Bone survival: The effects of sedimentary abrasion and trampling on fresh and cooked bone. Int J Osteoarchaeol 2(1):79–90. https://doi.org/10.1002/oa.1390020110

Nicosia C, Stoops G (2017) Archaeological Soil and Sediment Micromorphology. John Wiley & Sons Ltd. https://doi.org/10.1002/9781118941065

Opravil E (1952) The vegetation. Pavlov i, Excavations 1953:175–180

Oste JTF, Rodríguez-Berriguete Á, Dal' Bó PF (2021) Depositional and environmental controlling factors on the genesis of Quaternary tufa deposits from Bonito region, Central-West Brazil. Sediment Geol 413:105824. https://doi.org/10.1016/j.sedgeo.2020.105824

Patania I, Goldberg P, Cohen DJ, Wu X, Zhang C, Bar-Yosef O (2019) Micromorphological analysis of the deposits at the early pottery Xianrendong cave site, China: formation processes and site use in the Late Pleistocene. Archaeol Anthropol Sci 11(8):4229–4249. https://doi.org/10.1007/s12520-019-00788-6

Pentecost A (1995) The quaternary travertine deposits of Europe and Asia Minor. Quatern Sci Rev 14(10):1005–1028. https://doi.org/10.1016/0277-3791(95)00101-8

Pentecost A (2005a) The Travertine Fabric. In: Pentecost A (ed) Travertine. Springer Netherlands, pp 19–48. https://doi.org/10.1007/1-4020-3606-X_3

Pentecost A (2005b) Travertine. Springer Science & Business Media

Perri E, Manzo E, Tucker ME (2012) Multi-scale study of the role of the biofilm in the formation of minerals and fabrics in calcareous tufa. Sed Geol 263–264:16–29. https://doi.org/10.1016/j.sedgeo.2011.10.003

Pitarch Martí A, d'Errico F, Turq A, Lebraud E, Discamps E, Gravina B (2019) Provenance, modification and use of manganese-rich rocks at Le Moustier (Dordogne, France). PLoS One 14(7):e0218568. https://doi.org/10.1371/journal.pone.0218568

Portero García JM, Ramírez del Pozo J (1976) Mapa Geológico 1:50.000 y Memoria Explicativa. Hoja Nº Q33 (Comillas)

Posth C, Yu H, Ghalichi A, Rougier H, Crevecoeur I, Huang Y, … Krause J (2023) Palaeogenomics of Upper Palaeolithic to Neolithic European hunter-gatherers. Nature 615(7950):117-126. https://doi.org/10.1038/s41586-023-05726-0

Rentzel P, Nicosia C, Gebhardt A, Brönnimann D, Pümpin C, Ismail-Meyer K (2017) Trampling, Poaching and the Effect of Traffic. In Archaeological Soil and Sediment Micromorphology (pp. 281–297). https://doi.org/10.1002/9781118941065.ch30

Roldán RB, Rogina PMS, Gabiola BB, Mier LI (1985) Informe sobre el santuario rupestre paleolítico de la Fuente del Salín (Muñorrodero, Val de San Vicente, Cantabria). Boletín cántabro de espeleología (6):81–98

Sanchez-Martínez J, Mora Torcal R, Martínez-Moreno J (2021) Re-evaluating the Gravettian technocomplex in Iberia: The 497C lithic assemblage from Cova Gran de Santa Linya (Southeastern

Pyrenees). Quatern Int 587–588:41–61. https://doi.org/10.1016/j.quaint.2020.08.029

Scheer A (1993) The organization of lithic resource use during the Gravettian in Germany. Before Lascaux. The Complex Record of the Early Upper Paleolithic. CRC Press, Boca Raton, 193–210

Schiegl S, Goldberg P, Pfretzschner H-U, Conard NJ (2003) Paleolithic burnt bone horizons from the Swabian Jura: Distinguishing between in situ fireplaces and dumping areas. Geoarchaeology 18(5):541–565. https://doi.org/10.1002/gea.10080

Schilt F, Verpoorte A, Antl W (2017) Micromorphology of an Upper Paleolithic cultural layer at Grub-Kranawetberg, Austria. J Archaeol Sci Rep 14:152–162. https://doi.org/10.1016/j.jasrep.2017.05.041

Schmidt I, Zimmermann A (2019) Population dynamics and socio-spatial organization of the Aurignacian: Scalable quantitative demographic data for western and central Europe. PLoS One 14(2):e0211562. https://doi.org/10.1371/journal.pone.0211562

Scholl DW, Taft WH (1964) Algae, contributors to the formation of calcareous tufa, Mono Lake, California. J Sediment Res 34(2):309–319. https://doi.org/10.1306/74d71041-2b21-11d7-8648000102c1865d

Sellami F (2009) Les processus de formation, conservation et évolution des dépôts quaternaires sur les granites de Mêda-Escalhão: Olga Grande 4 et 14 de Pedras Altas. 200 séculos da história do Vale do Côa: Incursões na vida quotidiana dos caçadores artistas do Paleolítico [Trabalhos de Arqueologia, 52] 52:109–112

Shahack-Gross R, Bar-Yosef O, Weiner S (1997) Black-Coloured Bones in Hayonim Cave, Israel: Differentiating Between Burning and Oxide Staining. J Archaeol Sci 24(5):439–446. https://doi.org/10.1006/jasc.1996.0128

Shillito L-M, Matthews W (2013) Geoarchaeological investigations of midden-formation processes in the Early to Late Ceramic Neolithic levels at Çatalhöyük, Turkey ca. 8550–8370 cal BP. Geoarchaeology 28(1):25–49. https://doi.org/10.1002/gea.21427

Sievers C, Backwell L, Francesco dE, Wadley L (2022) Plant bedding construction between 60,000 and 40,000 years ago at Border Cave, South Africa. Quat Sci Rev 275:107280. https://doi.org/10.1016/j.quascirev.2021.107280

Sievers C (2013) Sedges as bedding in Middle Stone Age Sibudu (Doctoral dissertation, University of the Witwatersrand, Faculty of Science)

Simöes CD (2019) La formación de concheros en el litoral atlántico ibérico durante el mesolítico: perspectivas geoarqueológicas y micromorfológicas sobre las adaptaciones costeras de los cazadores-recolectores del holoceno (Doctoral dissertation, Universidad de Cantabria)

Simon U, Händel M, Einwögerer T, Neugebauer-Maresch C (2014) The archaeological record of the Gravettian open air site Krems-Wachtberg. Quatern Int 351:5–13. https://doi.org/10.1016/j.quaint.2013.08.009

Simonet A (2017) Gravettians at Brassempouy (Landes, France), 30,000 BP: a semi-sedentary territorial organization? World Archaeol 49(5):648–665. https://doi.org/10.1080/00438243.2017.1359109

Sorensen AC (2024) Lucky strike: testing the utility of manganese dioxide powder in Neandertal percussive fire making. Archaeol Anthropol Sci 16(8):134. https://doi.org/10.1007/s12520-024-02047-9

Soressi M, Rendu W, Texier JP, Daulny L, d'Errico F, Laroulandie V, … Tillier A-m (2008) Pech-de-l'Azé I (Dordogne, France): nouveau regard sur un gisement moustérien de tradition acheuléenne connu depuis le XIXe siècle. Les sociétés Paléolithiques d'un grand Sud-Ouest: nouveaux gisements, nouvelles méthodes, nouveaux résultats, 95–132

Stephens M, Rose J, Gilbertson DD (2017) Post-depositional alteration of humid tropical cave sediments: Micromorphological research in the Great Cave of Niah, Sarawak, Borneo. J Archaeol Sci 77:109–124. https://doi.org/10.1016/j.jas.2016.01.015

Stoops G, Marcelino V, Mees F (2010) Interpretation of Micromorphological Features of Soils and Regoliths. https://doi.org/10.1016/C2009-0-18081-9

Stoops G (2020) Guidelines for Analysis and Description of Soil and Regolith Thin Sections. https://doi.org/10.1002/9780891189763

Suchý V, Zachariáš J, Tsai H-C, Yu T-L, Shen C-C, Svetlik I, … Machovič V (2019) Relict Pleistocene calcareous tufa of the Chlupáčova sluj Cave, the Bohemian Karst, Czech Republic: A petrographic and geochemical record of hydrologically-driven cave evolution. Sediment Geol 385:110-125. https://doi.org/10.1016/j.sedgeo.2019.03.014

Svoboda J (2013) Gravettian art of Pavlov I and VI: an aggregation site and an episodic site compared. Palethnologie. Archéologie et sciences humaines, (5)

Taller A, Kieselbach P, Conard NJ (2019) Reconstructing technology, mobility and land use via intra- and inter-site refits from the Gravettian of the Swabian Jura. Archaeol Anthropol Sci 11(9):4423–4435. https://doi.org/10.1007/s12520-019-00778-8

Toffolo MB, Boaretto E (2014) Nucleation of aragonite upon carbonation of calcium oxide and calcium hydroxide at ambient temperatures and pressures: a new indicator of fire-related human activities. J Archaeol Sci 49:237–248. https://doi.org/10.1016/j.jas.2014.05.020

Trinkaus E (2005) The adiposity paradox in the Middle Danubian Gravettian. Anthropologie (1962-) 43(2/3):263–272

Vandiver PB, Soffer O, Klima B, Svoboda J (1989) The origins of ceramic technology at Dolni Věstonice, Czechoslovakia. Science 246(4933):1002–1008

Vazquez-Urbez M, Arenas C, Pardo G (2012) A sedimentary facies model for stepped, fluvial tufa systems in the Iberian Range (Spain): the Quaternary Piedra and Mesa valleys. Sedimentology 59(2):502–526. https://doi.org/10.1111/j.1365-3091.2011.01262.x

Vignoles A, Banks WE, Klaric L, Kageyama M, Cobos ME, Romero-Alvarez D (2021) Investigating relationships between technological variability and ecology in the Middle Gravettian (ca. 32–28 ky cal. BP) in France. Quat Sci Rev 253:106766. https://doi.org/10.1016/j.quascirev.2020.106766

Villagran XS, Poch RM (2014) A new form of needle-fiber calcite produced by physical weathering of shells. Geoderma 213:173–177. https://doi.org/10.1016/j.geoderma.2013.08.015

Villagran XS, Strauss A, Miller C, Ligouis B, Oliveira R (2017b) Buried in ashes: Site formation processes at Lapa do Santo rockshelter, east-central Brazil. J Archaeol Sci 77:10–34. https://doi.org/10.1016/j.jas.2016.07.008

Villagran XS, Huisman DJ, Mentzer SM, Miller CE, Jans MM (2017a) Bone and Other Skeletal Tissues. In Archaeological Soil and Sediment Micromorphology (pp. 9–38). https://doi.org/10.1002/9781118941065.ch1

Villaverde V, Sanchis A, Badal E, Bel MÁ, Bergadà MM, Eixea A, … Wild EM (2021) Cova de les Malladetes (Valencia, Spain): New Insights About the Early Upper Palaeolithic in the Mediterranean Basin of the Iberian Peninsula. J Paleolithic Archaeol 4(1):5. https://doi.org/10.1007/s41982-021-00081-w

Wadley L, Sievers C, Bamford M, Goldberg P, Berna F, Miller C (2011) Middle Stone age bedding construction and settlement patterns at Sibudu, South Africa. Science 334(6061):1388–1391. https://doi.org/10.1126/science.1213317

Wadley L, Esteban I, de la Peña P, Wojcieszak M, Stratford D, Lennox S, … Sievers C (2020) Fire and grass-bedding construction 200 thousand years ago at Border Cave, South Africa. Science 369(6505):863-866. https://doi.org/10.1126/science.abc7239

Walton J (1951) Occupied Rock-Shelters in Basutoland. S Afr Archaeol Bull 6(21):9–13. https://doi.org/10.2307/3887373

Wilson CA (2017) Electron Probe X-ray Microanalysis (SEM-EPMA) Techniques. In Archaeological Soil and Sediment Micromorphology, pp 451–459. https://doi.org/10.1002/9781118941065.ch43

Yravedra J, Álvarez-Alonso D, Estaca-Gómez V, López-Cisneros P, Arrizabalaga Á, Elorza M, … Uzquiano P (2017) New evidence of bones used as fuel in the Gravettian level at Coímbre cave, northern Iberian Peninsula. Archaeol Anthropol Sci 9(6):1153-1168. https://doi.org/10.1007/s12520-016-0317-0