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RESEARCH

Intra-site Organization of the Repeated Neanderthal Occupation of Unit A9, Grotta di Fumane (Pre-Alps, Italy)

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Abstract
The repeated use of spaces has been extensively studied for many years in Paleolithic archaeology through various disciplines and techniques. Caves and rockshelters are typically the most suitable contexts for these studies due to their characteristics. However, certain key elements make deciphering these reoccupations possible, which would otherwise be difficult, if not impossible. Among these elements, the density of archaeological materials and the presence of combustion features emerge as key to unravel occupation events at a site. This study focuses on Unit A9, a late Middle Paleolithic (MIS3) context with Mousterian featured by Discoid technology, which provides a high-resolution record of both archaeological materials and combustion features. In this study, these records have been combined with paleotopographic reconstructions, spatial studies, and archaeostratigraphy to interpret how space was managed by the Neanderthal groups that visited the cave during Unit A9. The results allow us to identify at least two separate phases of occupation of the cave, which occurred during the same seasons and with an organized management of space maintained over time.

Keywords Palaeotopographic reconstruction · Archaeostratigraphy · Spatial analysis · Neanderthals · Cave

Introduction

Spatial studies in Paleolithic contexts have become essential for the contextualization and comprehensive understanding of archaeological and paleontological localities, especially through a multiproxy approach where different disciplines converge. Recent advances in Geographic Information Systems (GIS) have significantly renewed spatial studies in Paleolithic contexts, revealing the variability in human behavior, different uses of space by humans and other animals, the complexities of multidisciplinary

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analysis, and the challenges and limitations inherent in such investigations (De la Torre and Benito-Calvo, 2013; Roy Sunyer, 2015; Geiling *et al.*, 2016; García-Moreno *et al.*, 2016; Martínez-Moreno et al., 2016, 2019; Sánchez-Romero et al., 2020, 2022; Thatcher *et al.*, 2017; Spagnolo et al., 2019, 2020a, 2020b; Mora *et al.*, 2020; Zilio et al., 2021; Deschamps *et al.*, 2022; Arteaga-Brieba et al., 2023; Gabucio et al., 2023; Sossa-Rios *et al.*, 2024, *inter alia*).

L. R. Binford described combustion features (*i.e.*, hearths) as elements in the structuring of space and activities across numerous ethnographic examples, such as the Mask site, Clean Lady at Kongumuvuk Creek or Tulukkana site (Binford, 1978a, 1978b, 1983). Similarly, J. F. O'Connell illustrated the use of fire by Hadza people in base camps or kill-butchering sites for specific activities (O'Connell et al., 1988a, 1988b, 1992). J. E. Yellen's studies of!Kung San groups (Yellen, 1977) showed that domestic activities were structured around hearths, while more specific activities, which generated more residues or required more space, took place away from the hearths. These patterns, or *schemes*, have been widely applied in Paleolithic archaeology to infer and mirror the behavior of hunter-gatherer groups using spatial analysis (Leroi-Gourhan and Brezillon, 1966; Leroi-Gourhan et al., 1972; Vaquero & Pastó, 2001; Vallverdú et al., 2010, 2012; Chacón *et al.*, 2015; Spagnolo *et al.*, 2016, 2019; Gabucio et al., 2017; Thatcher *et al.*, 2017; Bargalló et al., 2020; Deschamps *et al.*, 2022; Clark, 2023, *inter alia*) and the study of combustion features (Meignen et al., 2007; Goldberg et al., 2012; Mallol et al., 2013, 2019; Mentzer, 2014; Marcazzan et al., 2022, 2023; Herrejón-Lagunilla et al., 2024, *inter alia*).

Grotta di Fumane, a key Middle Paleolithic site (Peresani, 2022), has been the focus of numerous publications that have unveiled important aspects of Neanderthal behavior and lifestyle, such as the use of ornamental feathers (Peresani et al., 2011a) and fossil shells (Peresani et al., 2013), variability in lithic technology (*i.e.*, Delpiano et al. 2018 2017), the use of bone retouchers (Martellotta et al., 2020), and the high number and evolution of combustion features, sometimes overlapping in the same locations (Marcazzan et al., 2023). However, no comprehensive spatial studies integrating these data have been carried out until now. The only previous spatial study at Grotta di Fumane was carried out in Unit BR6 (Cremaschi et al., 2002), which applied GIS to analyze the distribution of lithic artifacts, bones, and combustion features, leading to the interpretation that the combustion features had been repeatedly used for processing and consumption activities.

In 2022, a more comprehensive spatial analysis study of Unit A9 was presented at the University of Ferrara, using GIS to integrate data on the spatial distribution of lithic artifacts and bones, and their relation to the arrangement of combustion features (Govoni, 2022). The present work stems from this study (Govoni, 2022), incorporating paleotopographic reconstructions, spatial analysis of specific variables and combustion features (Marcazzan et al., 2023), and archaeostratigraphy.

Grotta di Fumane

The cave is located at 350 m a.s.l. in the western Monti Lessini, one of the high plateaus of the Veneto Pre-Alps (northeastern Italy), making it a strategic point within the Fumane Valley. The complex of cavities where Grotta di Fumane is located was partially explored in the 1990 s and preserves a sedimentary sequence 12 m thick, which can be divided into four main macro-units: S, BR, A and D. Macro-unit A (from A13 to A1) shows the most intense human activity during MIS 3 and includes Unit A9, the focus of this study (Fig. 1). This stratigraphic sequence covers the crucial transitional period of the final Mousterian, Uluzzian and Proto-aurignacian levels, embedded within a finely layered sedimentary succession of frost-shattered slabs, aeolian silts and sands (Peresani, 2022 and references therein). The cave is composed of three tunnels carved into the micritic bank: a western gallery (tunnel A), a large central tunnel (tunnel B) and a smaller, still unexplored gallery at the eastern wall of tunnel B (tunnel C) (Peresani et al., 2011b) (Fig. 1). Due to rock-collapse and freezing–thawing degradation, the

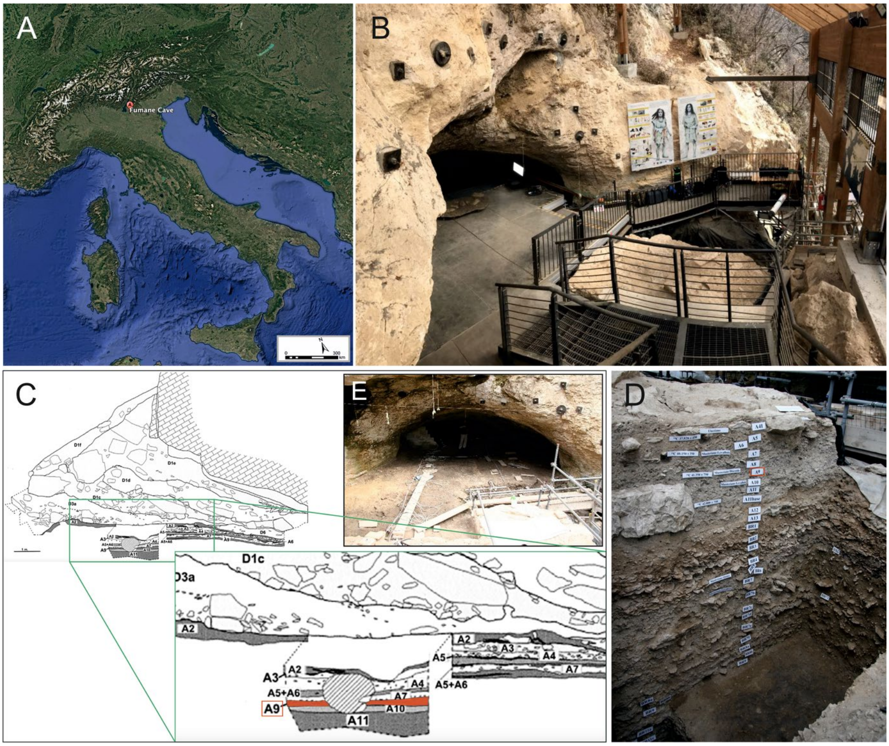

Fig. 1 Location and stratigraphy of Grotta di Fumane. **A** General location. **B** General view of the cave with the entrance to the small Tunnel C. **C** Stratigraphic sequence (modif. from Romandini et al., 2014). **D** Photo of the stratigraphic sequence as seen in the test pit. **E** Photo of the entrance to Grotta di Fumane with the main cave (Tunnel B) and Tunnel A on the left, allowing real dimensions of the cave to be seen (Tunnel C opens at the left corner of Tunnel B)

original roof of the cave, particularly in tunnel C, was modified during MIS 3 and MIS2.

A9 is a succession of thin layers and lenses, overlapped over a total thickness of 15–20 cm, mainly composed of frost-shattered slabs, aeolian silts and sands, and dark sediments resulting from an intense anthropogenic accumulation. During the excavation, this unit was divided into anthropogenic subunits (A9, A9I, and A9II), clast-supported subunits (A9BR and A9BRI) and matrix-supported layers (A9 sabbieI and A9 sabbieII). However, these subunits do not cover the entire surface of the cave. In the eastern area, near the cave wall, A9 covers A9BR, which is rich in anthropogenic material at its base, particularly in the southern part, and rests on top of Unit A10. In the western area, the excavators noted a loose clast-supported sub-unit, A9BRI, which is not in stratigraphic relation to A9BR. In this area, A9 splits into three anthropogenic subunits (A9, A9I, and A9II), which are rich in charcoal and other cultural remains. These subunits are composed of sandy-loamy fine fraction and limestone fragments, which prevail in the matrix toward the inner part of the cave. A9 lies on the top, while A9I and A9II are at the base of the Unit, directly on top of A10. Clear interfaces separate these three subunits, which were labelled A9 sabbieI and A9 sabbieII. These subunits are rich in sand and loose limestone fragments, with sub-horizontal bedding. The thickness and continuity of these anthropogenic subunits decrease from the cave wall toward the center. A9 and A9I form a palimpsest that overlies A9 sabbieII, with the latter extending slightly further east. Across the dripline in the southwestern area, the transition from the present-day sheltered space to the external area shows a change in the lithological features of A9, consisting in a higher sand content and an increasing proportion of silt. The chronological position of Unit A9 needs refinement, as it lies between the minimum radiocarbon age of 47.6 ka cal BP (Higham et al., 2014; Peresani et al., 2008) and the lower chronological boundary of layer A5 + A6 at 44.8 ky cal BP (Higham et al., 2009; Peresani et al., 2008).

The lithic assemblage in A9 is mainly a Discoid assemblage, dominated by different types of chert, such as Scaglia Rossa, Scaglia Variegata, and Maiolica, as well as other flints classified as Eocene (Tertiary) and Oolitic (Tenno Formation), all sourced within a radius of about 10 km around the site (Delpiano et al., 2018). The assemblage includes thick flakes, pseudo-Levallois points, core–edge removal flakes, and retouched artifacts, such as scrapers, backed pieces, denticulates, notches and pointed tools, and bone retouchers (Delpiano & Peresani, 2017; Delpiano et al., 2018; Martellotta et al., 2020). Functional analyses have provided insight into some of the activities carried out in the cave, such as the use of brute flakes and retouched tools for scraping or cutting fresh and dry skins and wood (Delpiano et al., 2019a; Lemorini et al., 2003).

The fauna assemblage is dominated by cervids (80%), followed by bovids and caprids (15%). Other species, such as marmot, fox, bear, hyena, or wild boar, represent around 5% of the assemblage (Romandini et al., 2014; Terlato et al., 2019). Birds are also a relevant component of the assemblage (Fiore et al., 2016; Romandini et al., 2016). The A9 ungulate assemblage indicates exploitation of young, young adult, and adult prey, from late summer to winter as documented by cementochronology and use-wear combined analyses of herbivore teeth (Livraghi et al., 2025; Romandini et al., 2014). These data are consistent with the recently published detailed study on micromorphology of the Grotta di Fumane deposit, which indicates a dry and/or warm phase during the formation of A9 (Kehl et al., 2025). Various butchering actions, including skinning, dismembering, filleting, and bone breaking, were identified, along with evidence of the use of diaphyseal bone fragments as retouchers for flint tools (Martellotta et al., 2020). Some skeletal elements, such as radii, were intentionally selected for specific retouching tasks, such as oblique retouch typical of scrapers. However, bone retouchers were not used intensively or continuously (Martellotta et al., 2020).

Previous spatial analyses of A9 focused on the distribution of bird bones (Romandini et al., 2016), bone retouchers (Martellotta et al., 2020), combustion features (Marcazzan et al., 2023), and bone refits (Modolo et al., 2025). These studies contributed to understanding the use of Grotta di Fumane by Neanderthal groups. Nevertheless, it was only with the work of Govoni (2022) that a more focused and advanced approach to spatial analysis has been applied. Govoni's work addressed the spatial distribution of lithic artifacts and bones in relation to the cave's morphology and the presence of numerous combustion features, applying spatial analysis and geostatistics methods based on Geographic Information Systems (GIS). This study provided insights into the distribution of the artifacts left by Neanderthal groups who visited Grotta di Fumane and offered initial approximations of space organization.

The present work stems from Govoni's (2022) master's thesis and expands with the paleotopographic reconstruction of Unit A9, archaeostratigraphic analysis, and detailed information on the combustion features (Marcazzan et al., 2023). Furthermore, field observations made during the 2009–2010 excavations (Peresani, 2009), when the entire A9 excavation surface was exposed for topographic mapping, have been incorporated.

Materials and Methods

The first archaeological excavations were conducted at various intervals through trenches and limited sectors. More extensive excavations, covering 68 m^2 took place at the entrance of the cave between 2009 and 2013. The recording method followed in these campaigns included mapping all lithics > 3 cm, bones > 5 cm, and teeth using a total station. The small size of most artifacts, coupled with the fact that most flakes were equidimensional due to the Discoid technology method characteristic of this lithic assemblage, made recording orientation and slope useless. Thus, these data were not considered for this spatial study. Smaller fragments, micromammals, and small avifaunal bones were recovered through wet sieving. The topography of the units was recorded with a total station, generating a grid with points taken every 10 cm.

The first step before addressing the spatial analysis was the paleotopographic reconstruction of Unit A9. However, we only had centimeter-accurate GPS points for the exposed surface of A9 of the eastern excavation zone, and no such points for the western zone. We used Kriging ordinary to reconstruct the excavation zone where we had topographic points, and the parameter *mean* to reconstruct the western zone using XYZ data derived from the recorded items. In total, 925 topographic points were used for the reconstruction of the eastern zone, and 2494 points for the western zone. This geostatistical procedure is an interpolation method that allows the reconstruction of the paleogeography (Oliver, 1990) and has proven to be very useful for estimating the paleotopography where artifacts were deposited (Bargalló et al., 2020; De la Torre & Wehr, 2018; Giusti et al., 2018; Sánchez-Romero et al., 2020, 2023). In this way, we can infer whether the accumulation of artifacts was determined by such relief (Sánchez-Romero et al., 2022). To evaluate and validate this method, we reconstructed the eastern area using XYZ data from the recorded features and compared it with the result obtained using the *real* GPS topographic points. The comparison was performed using the function *raster calculator* (ArcGIS 10.8.2) to quantify the differences between the two rasters: the *real* with GPS points and the *inferred* with XYZ data obtained from the recorded artifacts.

In Govoni (2022), Kernel Density Analysis (KDE) was performed on lithics and bones (see SI1). In the present study, we extended the analysis to different categories within these two variables. KDE was applied to retouched lithic tools ($n = 166$), burned lithics ($n = 225$), bone retouchers ($n = 38$), burned bones ($n = 124$), and bones with evidence of cutmarks ($n = 284$) (note that bone retouchers also show cutmarks). In total, 2774 lithics, 782 bones, 32 burned stones, and 1059 charcoal fragments were analyzed. This method has been widely used in Paleolithic contexts (as referenced in the Introduction) and provide a good graphic representation of the areas with higher accumulation of elements by applying a Kernel function to calculate the magnitude of elements per unit area (Sánchez-Romero et al., 2022). We applied a search radius of 1 m for all categories, except for bone retouchers due to the characteristics of their distribution (see SI1).

To evaluate whether the bone and lithic assemblages were dispersed, clustered, or randomly distributed, and as a preliminary step before the identification and analysis of singular clusters highlighted by KDE, we applied two general statistical methods to determine the distribution of the elements. Ripley's K Function evaluates the dispersion or clustering of elements (Ripley, 1976), indicating statistically significant concentrations within a distance interval. This test calculates the average distance between elements within determined distance bands to find the highest concentration of materials (Sánchez-Romero et al., 2022). Ripley's K Function is particularly useful for analyzing how the clustered or dispersed nature of the assemblage changes at different distances. In this work, we applied 99 permutations and a distance band of 10 (Govoni, 2022). In addition, to verify and contrast the results from Ripley's K Function, Average Nearest Neighbor (ANN) test was applied (Govoni, 2022). This test measures the distance between each element's centroid and the location of its closest neighbor centroid, calculating the average of all these closest or nearest neighbor distances (Getis, 1964). Both tests indicated a clustered nature of the assemblage (see Results). Therefore, a local method of analysis was applied to define local clusters and to evaluate the correspondence with the concentrations identified by KDE. Thus, Getis-Ord Gi* (Getis & Ord, 1992) was applied to the "weight" variable of the bones, since the measurements of the lithic industry were not available and the measurements of the bones were classified by intervals, which significantly reduces the precision in this type of calculations. This test identifies statistically significant clusters, both high (hot) and low (cold) values, based on a quantitative variable (in this case "weight") (Getis & Ord, 1992; Sánchez-Romero et al., 2022; Siabato & Guzmán-Manrique, 2019).

The archaeostratigraphic analysis involved the delimitation of five sections, four running north–south and one northeast-southwest. These sections were delineated based on two primary criteria: number of elements and number of combustion features. In this way, the archaeostratigraphic sections were delimited based on concentration of elements (bones, lithics, charcoal, *etc.*) and combustion features were most abundant. Considering the number and distribution of elements, as well we the location of the combustion features, each section was 0.5 m thick with variable lengths depending on the characteristics of the area to cover.

The combustion features were studied and published by Marcazzan et al. (2023) and were essential for the analysis and identification of subunits within A9. These features were plotted in ArcGIS 10.8.2, in both 2D and 3D, and cross-referenced with the archaeostratigraphic sections delimited by the assemblage characteristics. Once the combustion features were analyzed, along with the archaeostratigraphic sections, we separated the accumulations and the combustion features that were clearly assignable to specific sublevels. Although the original numbering of the features uses Roman numerals, here, we have adopted Arabic numerals to facilitate reading and identification.

Results

Paleotopographic Reconstruction

The paleotopographic reconstruction of the eastern area was based on XYZ data from GPS points and from archaeological items recorded by a total station. The comparison of these two methods allowed to evaluate the use of archaeological item data as an alternative when GPS data is not available. Figure 2 shows the reconstruction of the eastern area and the differences between the two methods, with almost identical results with some differences at specific points (Fig. 2). Based on this comparison, we reconstructed the paleotopography of the western zone using the XYZ data from the recorded items (Fig. 2). This allowed us to observe a continuous surface of A9, except for the trench excavated in the 1990 s, which separates the two areas (Fig. 2).

When the artifacts were plotted onto the A9 paleotopography, we observed that the main bone accumulation in the eastern part of the cave coincides with a depression in the paleotopography. This depression is almost aligned with the position of one of the cave's galleries (tunnel C) (Fig. 3).

Spatial Distribution

The results obtained by applying the statistical tests Ripley's K Function and ANN indicate a clearly clustered nature of the lithic and bone assemblages. In the case of Ripley's K Function, the observed and expected calculations never overlap (SI2), indicating the presence of more closely grouped objects than expected in a random

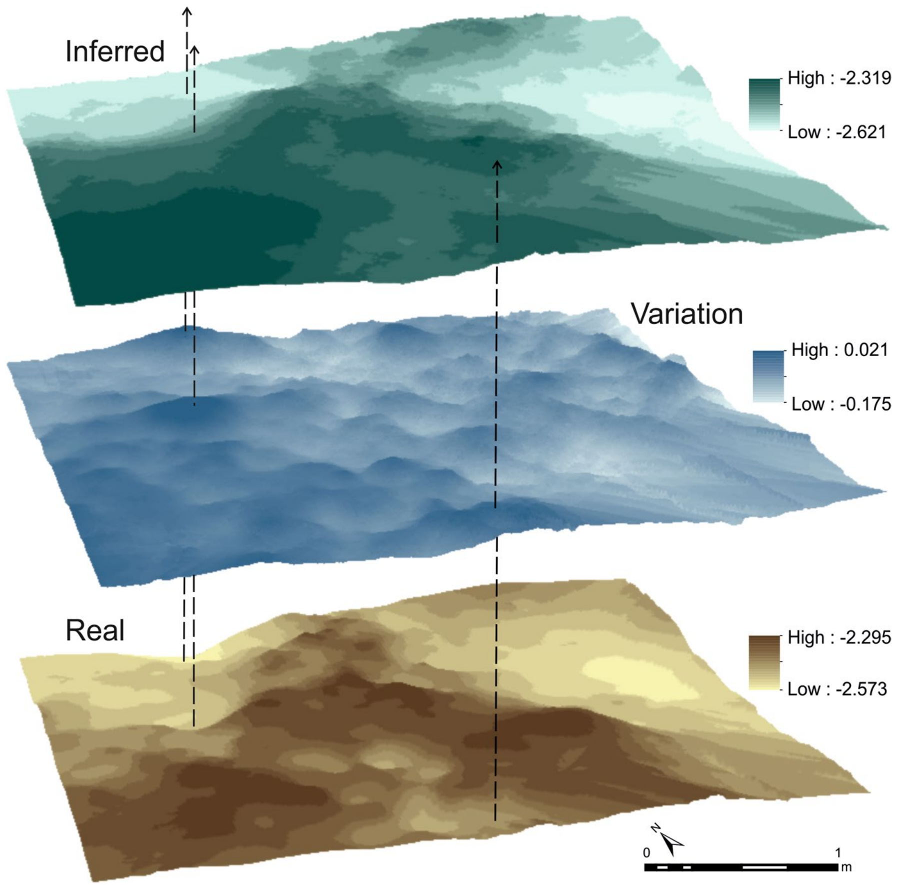

Fig. 2 Reconstruction of the eastern zone using GPS topographic points (real) and points from archaeological items recorded with total station (inferred), and their comparison. We can see the little variations (marked with arrows across all the reconstructions) between both paleotopographic reconstructions (variation), which do not affect the estimation of Unit A9 and the surface where the materials were deposited

scheme (Govoni, 2022). This positive association is consistent with the results from the ANN test, whose very low NN *Z*-score indicates a probability of less than 1% that these distributions were the result of randomness (Govoni, 2022).

The KDE analysis performed by Govoni (2022) identified several accumulations within the bone and lithic assemblages, which were analyzed separately. Six clusters were identified in the lithic assemblage, while only one cluster was identified in the bone assemblage (see SI1). A smaller accumulation of bones, with a KDE value matching the main bone accumulation, was also identified but was not considered for the analysis due to the small sample size. Bones are clearly accumulated on the eastern side of the cave, similar to the lithic assemblage, although the main accumulation of these (lithics) shows different spots of more density in what looks like an alignment, and in clear relation with the combustion features.

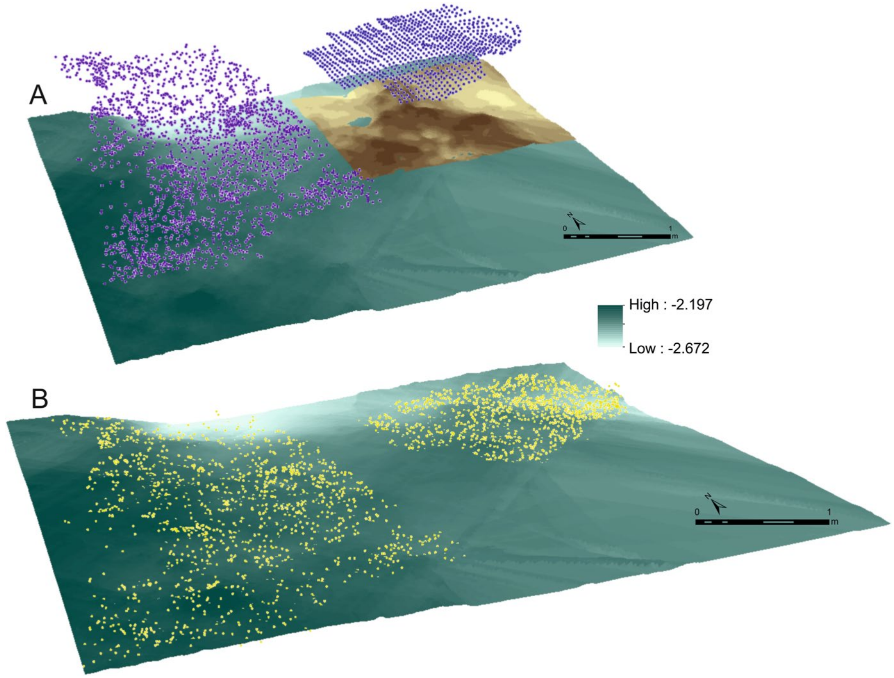

Fig. 3 Reconstructed paleotopography of Unit A9 joining both areas. **A** The points used for the reconstruction of the paleotopography of the eastern area and the difference between the inferred paleosurface and the one calculated with topographic points. **B** The entire reconstructed paleotopography of Unit A9 with all the A9 excavated elements on top. For the total paleotopographic reconstruction, we have applied *Resample* to smooth the surface and soften the edges resulting from the interpolation

When the subcategories of these elements are analyzed, very interesting patterns emerge. In the case of retouched tools and bone retouchers (Fig. 4), both subcategories coincide in the same area of the cave, in line with the observations made by Martellotta et al. (2020). Additionally, some of the retouched lithics are clearly related to some combustion features. A similar pattern is observed with burned bones and burned lithics. These two subcategories are more widely distributed across the cave and coincide in every spot of more accumulation, except in one case (Fig. 4) where an accumulation of burned lithics is not related to any accumulation of burned bones but is instead associated to some combustion features located at the entrance of the cave. Most accumulations of burned elements are associated to combustion features, except for one case located on the western wall of the cave. Some of the burned artifacts are scattered throughout other parts of the cave (see SI1), which could be the result of processes such as sweeping to clear some of the combustion features, activities that have dispersed some of the burned remains, or simply the passage of people who have shifted them to other parts of the cave. Regarding bones with cutmarks (see SI1), most of these are clearly accumulated in the same area where the main accumulations of bone retouchers and burned bones were identified (Fig. 4).

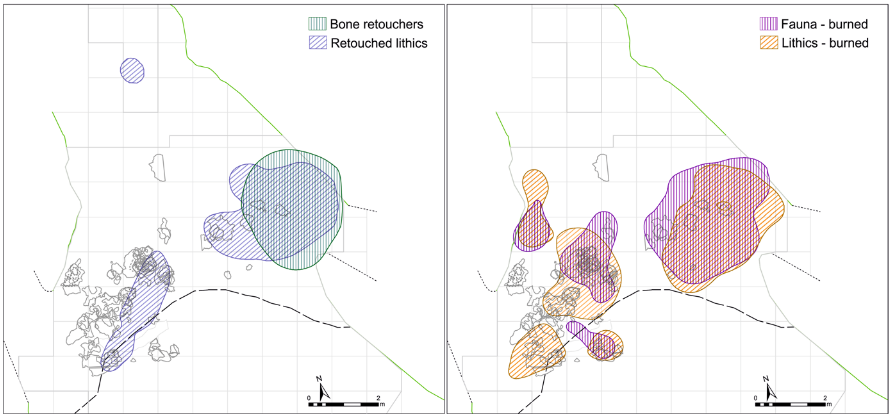

Fig. 4 Main accumulation areas identified by KDE (see SI1) of bone retouchers and retouched tools and of burned bones and burned lithics

The hotspot analysis performed on the weight of bones did not provide any relevant result suggesting a pattern in their accumulation (see SI2). Their accumulation appears random and does not respond to any pattern that might indicate intentionality or post-depositional factors that could have sorted their accumulation.

Regarding the distribution of combustion features, most are located at the entrance of the cave, rather than in the inner part. Of the 48 features, 15 of them were analyzed and classified as combustion features, such as fireplaces, rubified layers, and charcoal concentrations (CC): S3, S5, S8, S9, S10, S11, S12, S13, S15, S16, S17, S18, S21, S24, and S25 (Marcazzan et al., 2023). The remaining features were described according to field observations rather than micromorphological analysis (see SI4 for more information about the excavation of these features). All of these combustion features, analyzed by Marcazzan et al. (2023), provide very interesting information to complement the spatial study presented here. In the eastern zone of the excavation, where the main accumulations of lithics and bones are located, the number of combustion features is relatively low, in contrast with the high accumulation of elements in this area of the cave. There are five features, two of them identified as charcoal concentrations (S1 and S7) and three combustion features (S3, S5 and S6), arranged in a NESW alignment along the wider part of the cave, which seems to follow the natural morphology of the space. None of the features overlap. However, combustion features are more numerous in the central-western area, most of which are overlapping and with a considerably lower density of associated elements compared to the eastern area. The sizes of the combustion features identified in A9 vary from 10 to 20 cm in diameter to 1 m, with depths ranging from 1 to 10 cm, and various shapes (Marcazzan et al., 2023). Although charcoal is distributed throughout the area of A9, the main accumulations and other minor concentrations clearly follow the distribution of the hearths (see SI1), with the main accumulations associated to the hearths located in the western part of the cave.

Archaeostratigraphy

In total, five archaeostratigraphic sections were delimited and analyzed: four running north–south (PNS-1, PNS-2, PNS-2, PNS-4) and one northeast-southwest (PNESW). These sections cover most of the combustion features identified in A9, as well as the main accumulations of bones, lithic artifacts, and charcoals. At least two subunits were identified within A9:

PNS-1: This section is 4.10 m long and includes features S45, S15, S15a, S16b and S25, all identified as combustion features (Marcazzan et al., 2023). Features S15a, S16b, S15 and S25 are overlapped, with S15a and S16b clearly above S15 and S25, with gap or hiatus between these two groups of features (Fig. 5 and SI3). S45 is positioned separately; however, due to its position in the section, its relationship to the rest of the features, and considering the distribution of artifacts, S45 seems to belong to the same lower subunit as S15 and S25 (Fig. 5 and SI3). S45 is located in a lower position than S15 and S25, possibly due to the slope of the level. In this part of the site, there are hardly any objects to check the slope or geometry of this point of the level, and most of the objects are found above S45 (Fig. 5 and SI3). The charcoal concentration located in the northern part of the section seems to be related to S25, while the concentration of lithic artifacts and charcoal to the south does not correlate clearly with any feature; archaeostratigraphic analysis does not provide clear results about to which sublevel seems to belong to. Archaeostratigraphy suggests several gaps or hiatuses, indicating different episodes of material deposition. However, it is important to keep in mind that this part of the section is located at the entrance of the cave and might be influenced.

PNS-2: This section is 4.14 m long and includes features S32, S44, S48, S45 and S39, all of them identified as combustion features (Marcazzan et al., 2023). Section PNS-2 clearly shows the variation in the topography of Unit A9 and allows for the distinction of several sublevels corresponding to the position of the combustion features (Fig. 5 and SI3). Features S32 and S39 (a huge combustion feature described

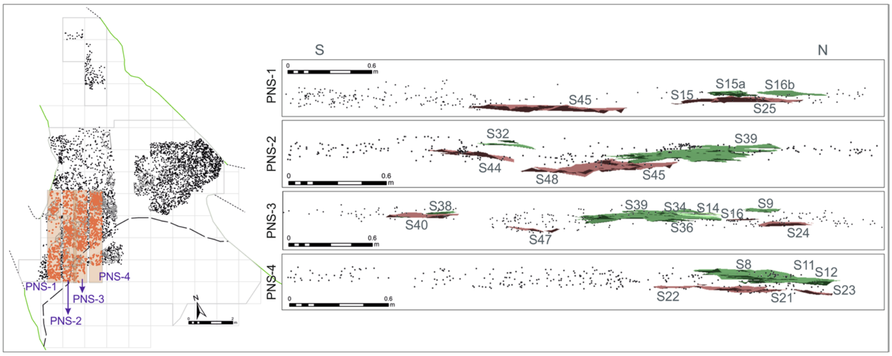

Fig. 5 Map of the location of the PNS archaeostratigraphic sections. Archaeostratigraphic sections with the subunits "Lower" and "Upper" differentiated by colors (red: "Lower", green: "Upper") in the combustion features. The numbers (S45, S32, S9, *etc.*) correspond to the identification number of the combustion features. See SI3 for more details

by Marcazzan et al. (2023) as a single dark layer, rich in organic matter and charcoal at the bottom of a rubified later) are located at the upper part of A9. In the lower part of A9, features S44, S48, and S45 are present, with S45 below S39. S48 and S45 are parallel and very closely positioned (Fig. 5 and SI3), which may indicate some kind of simultaneity. Some artifact accumulations are clearly associated with some combustion features, especially the charcoal accumulation related to S39 and the accumulation of lithic artifacts above S44 (Fig. 5; SI3 and SI4).

PNS-3: This section, 4.20 m long, shares one of the largest combustion features documented in A9 (S39) with PNS-2. This section comprises most of the features: S40, S38, S47 (CC), S39, S36, S34 (RL), S14 (eph.), S16, S9 and S24 (eph.) (Fig. 5; SI3 and SI4). They were all identified as combustion features, except for S34, identified as a rubified layer (RL), S47 as a charcoal concentration (CC), and S14 and S24 identified as "ephemeral" (eph.) (Marcazzan et al., 2023). These features are distributed along the section rather than being concentrated in a single point. S40 and S38 are located in the southern part of the section, S47 right in the middle, and then the remaining to the north. The lower part of A9 comprises S40, S47, S16, and S24, the latter in a lower position than the rest of features (Fig. 5 and SI3). The top subunit of A9 contains S38, S39, S36, S34, S14, and S9. Features S36, S34, and S14 are closely related; by observing it in 3D view, it is possible to establish the structures' sequence: with S36 likely being the earliest and the others following in sequence (first S34 and then S14). Probably all of them are associated with S39 due to their proximity (Fig. 5; SI3 and SI4). S16 seems to belong to the same subunit and sublevel as S40, as they are positioned along the same straight line and seem to align in the sequence of deposition of events, as indicated by the identified gaps or hiatus (Fig. 5 and SI3). S16 is located between S9 and S24, although this could be influenced by the morphology or slope of A9's topography. However, no remarkable changes are observed in the palaeotopography at this specific point. It is possible that we are also witnessing an *intermediate* event between what we have identified as the top-subunit and lower-subunit of A9. Additionally, we observe a charcoal accumulation clearly related to S16, and a concentration of lithic artifacts on the side of S39 (Fig. 5; SI3 and SI4), which allows distinguishing traceable gaps that seem to delimit some archaeostratigraphic sublevels.

PNS-4: This 3.40-m section includes S8, S11, S12, S22, S21, and S23 (eph.). All of them have been classified as combustion features, except for S23, classified as ephemeral; two different combustion layers were identified in S21 (Marcazzan et al., 2023). All features are located in the northern part of the profile and are overlapped (Fig. 5 and SI3). The features identified in the lower A9 subunit are S22, S21, and S23, and they seem to be contemporaneous with each other; S8, S11, and S12 belong to the top subunit (Fig. 5 and SI3). Two small accumulations of elements have been detected in this section, which, as also occurred in PNS-2, would have been interpreted as accumulations related to each other and belonging to the same occupation event or occurrence; however, as shown here, they correspond to different temporal events.

PNESW: This section, 8.50 m long and NESW direction, spans an extended area divided by the trench. As a result, this section was analyzed in two parts. The goal of tracing this section was to connect both sides of the trench, covering as many combustion features and artifacts as possible, and assessing the archaeostratigraphic correspondence between the two sides (Fig. 6 and SI3). The study of this section also provided a new perspective on section PNS-4, allowing us to double-check the relationship between combustion features and artifacts distribution.

PNESW-1: This part of the section includes features S1 (CC), S3, S5, S7 (CC) and S6. It is the only section where no overlapped features were observed, and two charcoal concentrations were identified (S1 and S7). The remaining features were identified as combustion features (Marcazzan et al., 2023). Feature S7 (CC) seems to be positioned lower than the others, while S6, although apparently aligned with S1 (CC) and S3 (Fig. 6 and SI3), is slightly tilted to the east, coinciding with the slope of the level at this point in the site (nearly aligning with the position of tunnel C) (Fig. 7). This section shows several gaps or hiatuses, which may indicate different moments of deposition of materials, most of which in perfect match with the position of the features. S1 (CC) and S3 are very close to each other and seem to belong to the same sublevel. However, while S5 seems to be above all the features, observing the archaeostratigraphy (Fig. 6 and SI3, Fig. S15) reveals that S6 would belong to a sublevel above S5, but affected by the slope of the level (SI3, Fig. S15). S7 (CC) seems to be in the same sublevel as S1 (CC) and S3.

PNESW-2: This part of the section includes S9, S16, S24 (eph.), S11, S8, S12, S21, and S22, all identified as combustion features, with S24 classified as ephemeral (Marcazzan et al., 2023). A clear separation between the superimposed features is observed (Fig. 6 and SI3). In addition to identifying gaps in artifacts distribution through archaeostratigraphy, the presence of at least two subunits in A9 is evident when the features are plotted. Thus, the lower subunit includes S16, S24 (eph.), S21, and S22, while the top subunit comprises S9 (above S16 and S24), S11, S8, and S12 (S8 and S12 clearly above S21 and S22) (Fig. 6 and SI3). As seen in PNS-2 and PNS-4, this part of the section contains two small concentrations of elements associated with different events: one linked to S12 in the top subunit, and another notable

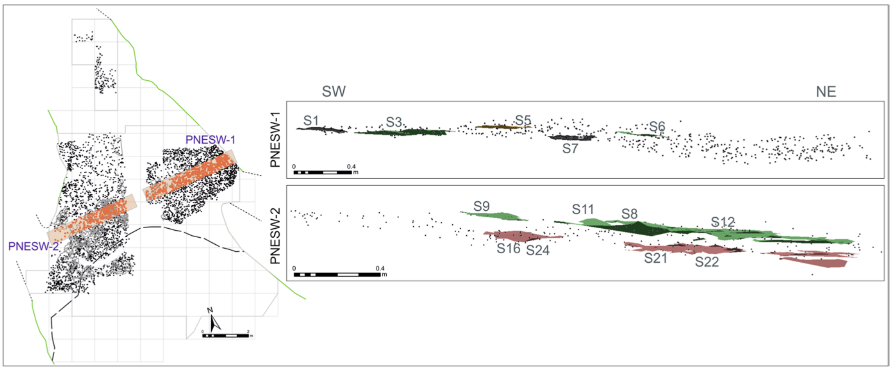

Fig. 6 Map of the location of the PNESW archaeostratigraphic sections. Archaeostratigraphic sections with the subunits “Lower” and “Upper” differentiated by colors (red: “Lower”, green: “Upper”) in the combustion features. The numbers (S1, S3, S5, *etc.*) correspond to the identification number of the combustion features. PNESW-2 includes the position of S10, S18, and S41, which are outside the limits of PNESW-2 but in close proximity (see SI3 for more details)

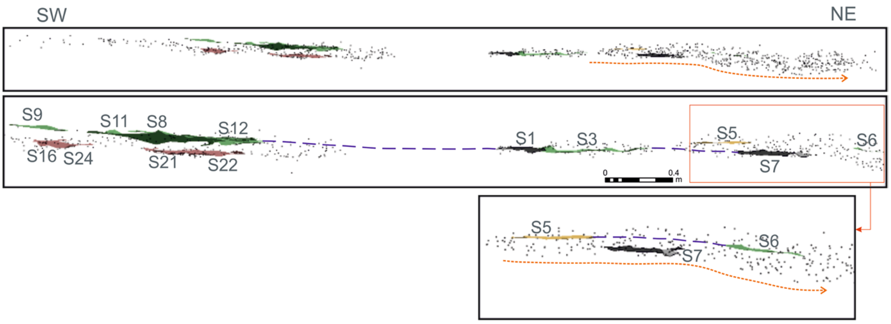

Fig. 7 Possible correspondence of the combustion features identified as "Upper" sublevel in PNWSE-2 (S9, S11, S8, and S12) with the position of features S1 (CC), S3, and S7 (CC) of PNWSE-1, as well as the evident slope near the gallery (tunnel C) that seems to affect the position of S6

accumulation associated with S21 and S22 in the lower subunit (Fig. 6 and SI3). We extended this profile slightly to examine the connection between these features and others located outside the limits of PNESW-2 (see SI3, Fig. S16), but in close proximity. This extension helps to determine the sequential correspondence of all the combustion features identified in A9 and to which subunit they belong. Thus, we have analyzed the position of S10, S18, and S41, all identified as combustion features (Marcazzan et al., 2023). As seen in Fig. 6 (and SI3), two subunits can be distinguished. Feature S10 is above S18 and S41, the latter associated with a concentration of charcoal and showing evidence of post-depositional alteration (Marcazzan et al., 2023). In the case of S18, it appears to represent several events, such as a burning or reuse sequence, with S18_3 at the base, followed by S18_2, and finally S18_1 as the last event (see SI3, Fig. S16). The position of S18_1 and S41 is similar, suggesting they may represent two parallel events.

When PNESW-1 and PNESW-2 are crossed and compared, features S1 (CC), S3, and S7 (CC) from PNESW-1 seem to correspond with the same top subunit as S9, S11, S8, and S12 from PNESW-2 (Fig. 7). Conversely, features S16, S24, S21, and S22 from PNESW-2 do not correlate with any of the features of PNESW-1; and features S5 and S6 seem to be positioned higher than the others (Fig. 7), which could indicate a distinct episode or event of activity/occupation/visit. This interpretation has to be taken with caution as the paleotopography and S6 suggest a slope of the A9 unit at this specific point of the site (Fig. 7). These results were then compared with field observations (SI3) to improve precision, especially where stratigraphic distinctions were difficult to make in the field.

Discussion

Grotta di Fumane is a high-resolution archaeological site with an impressive record that has provided insights into many aspects of human behavior, particularly that of Neanderthals (see Peresani, 2022, and the references therein). Previous studies have focused on different aspects of the archaeological record, but this work consolidates those findings to explore another key and interesting aspect of Neanderthal behavior: the dynamics of occupation and the organization of domestic space. This will allow us to infer the cognitive complexity of these groups, compare them with other Neanderthal groups and early modern humans, and contribute to the understanding of the evolution of behavioral aspects in the ongoing discussion about the transition to the Upper Paleolithic.

The deposit is minimally affected by burrows, which were delimited and excavated, as well as by a trench that splits the archaeological context. The paleotopographic reconstruction of both halves of the site has proven valuable for approximating the surface where artifacts were deposited, and the activities occurred. The test comparing the efficiency and accuracy of reconstructing the paleotopography using topographic points versus points from recorded archaeological objects showed that, in the absence of topographic data, the use of these objects as an alternative is a close approximation to what would be obtained from actual topographic data. The use of topographic tools to reconstruct Paleolithic surfaces has been successfully applied at other sites (De la Torre & Wehr, 2018; Sánchez-Romero, 2019; Sánchez-Romero et al., 2023), as well as the use of recorded materials data (Giusti et al., 2018; Sánchez-Romero et al., 2020). However, this is the first study to compare these two types of datasets to reconstruct the same area and test their efficiency. This approach allowed for the reconstruction of the surface of A9, obtaining an approximation of the surface where the artifacts were deposited. The A9 surface was found to be mostly flat (Fig. 3), except for a depression near one of the galleries (tunnel C) on the cave's eastern side (Fig. 3). This depression may have influenced the distribution of the objects in Unit A9.

The distribution of artifacts indicates several denser clusters of lithic materials, in clear association with combustion features in the western part of the cave. Although these delimited accumulations are related to combustion features, the main lithic accumulation is located toward the eastern wall, with only a few features associated, including a charcoal concentration. This pattern coincides with the distribution of bone remains, which are mainly accumulated in the eastern part of the cave, with only minor accumulations scattered elsewhere. The topography of this area shows a depression of the surface, which could be related to the nearby gallery (tunnel C). The proximity of the main lithic and bone accumulations to this depression raises the question of whether they were accumulated naturally due to the depression's topography, or whether they were intentionally placed here, perhaps as a secondary refusing area. These accumulations are located near tunnel C, close to the wall, and distant from the features and main occupation/activity area. It is interesting to highlight that this is the only part of the cave without overlapping features, and the number of features here is considerably lower compared to the rest of the cave. It is also the area where more ash and charcoal concentrations (CC) have been identified.

Classification by Subunits and Distribution of Combustion Features

The archaeostratigraphic analysis of the eastern part of the cave does not allow distinguishing subunits in the same way as the western part, where most of the combustion features are concentrated. The central and western parts of the cave present a high number of features, most of which overlap, but with considerably fewer artifacts (except in certain points where accumulations were detected) compared to the eastern part. In the central and western areas is where we were able to distinguish two subunits based on the position of the combustion features and the distribution of artifacts observed in the archaeostratigraphy. The map of combustion features, once assigned to the *upper* or *lower* subunit (Fig. 8), indicates a clear reuse of the space. This way, it is possible to observe that the features classified as "Upper" overlap with the "Lower" ones, suggesting a pattern of convenience or preference in the use of this part of the cave. This may be due to the type of activities conducted or even due to the cave's characteristics/geometry, such as space, light, *etc*.

This preference for using the outer parts of caves or rockshelters has been observed in other similar cases, such as Abric Romaní (level O), Amalda I, Teixoneres or Oscurusciuto (SU13) (Sánchez-Romero et al., 2020; Spagnolo et al., 2019;

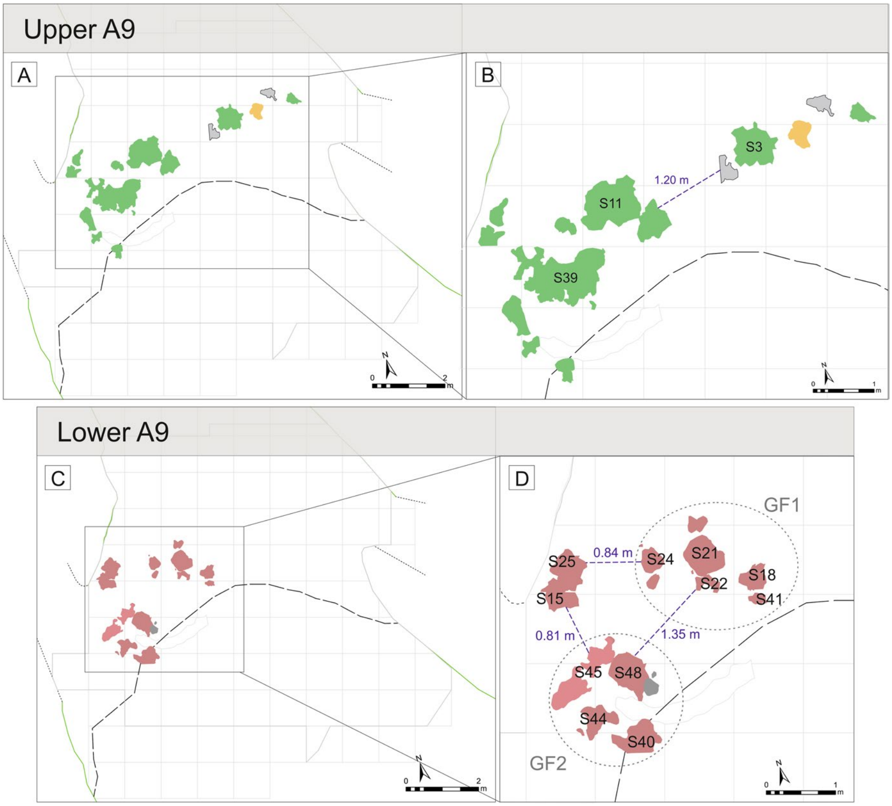

Fig. 8 Resulting map from separating the features by Lower (in red) and Upper (in green) (in yellow indicates the position of S5 on top of the features identified as "Upper"; in gray: ash/charcoal accumulations) subunits in A9. Calculation of distances between groups of features and the possible correspondence of features that would compose the groups GF1 and GF2 in the Lower subunit

Vallverdú et al., 2012; Zilio et al., 2021). These sites show that primary activities often took place near the cave entrance, which has been interpreted as a more efficient use of space or a way to capitalize on natural light. However, some researchers suggest that the location of hearths is determined by the air circulation, affecting both heat distribution inside the cave and smoke ventilation (Kedar & Barkai, 2019; Kedar et al., 2020). The location of hearths would depend largely on their characteristics and the original cave's morphology, with the time of year and the temperature difference between inside and outside being determining factors. In general, when hearths are located near the cave's back wall, smoke height increases (Kedar et al., 2020), making the cave more habitable. However, a recent study at Tor Faraj (Kedar et al., 2024) determined that short-duration daily activities likely occurred at the center and front of the rockshelter, where smoke density was too high for sleeping, and that the number of simultaneously active hearths was limited, even in large cavities with wide entrances (Kedar et al., 2024).

However, it is interesting to mention that the archaeostratigraphy of Unit A9 shows no combustion features toward the eastern area during the "Lower" subunit activities or occupation events. This may indicate that this area was not considered suitable for the maintenance of fire or other primary activities during this period. Recent studies have not evidenced extensive post-depositional alterations in this area of the cave (Kehl et al., 2025; Modolo et al., 2025). The eastern part of the cave is also interesting for potentially representing the last episode of occupation in A9. Combustion feature S5 is located slightly above the "Upper" subunit and the other features in this part of the cave. The morphology of S5 indicates that it is a flat feature, so its elevated position does not seem to be an effect of the slope, unlike feature S6, which is clearly affected by the slope of the unit. S5 is a well-defined combustion feature, flat (1 cm thick), rich in organic matter, with four sublayers, and containing charcoal and burned bones (Marcazzan et al., 2023). Given its position above the other features, unaffected by the slope of the unit, its more discreet position relative the other combustion features, and its good preservation without significant post-depositional alterations ("dark layer in rich organic matter with a grayish fine faction; a crown around the central part (…) and slightly sticky due to the presence of organic matter", Marcazzan et al., 2023), it is possible that S5 marks the last Neanderthal episode of activity or occupation at the cave before the site was abandoned, until the arrival of subsequent human groups.

The map of combustion features classified by subunits shows that the "Upper" subunit features located in the eastern part of the cave are clearly associated with charcoal concentrations, more specifically S3 with S1 (CC) and S6 with S7 (CC). These may indicate maintenance activities, such as controlling heat or ash dumping, as observed in other cases (Clark & Ranlett, 2022; Goldberg et al., 2009; Marcazzan et al., 2023; Meignen et al., 2007; Sánchez-Romero et al., 2024; White et al., 2017). These four features are aligned not only with each other but also with the other combustion features identified in the "Upper" subunit, although S3, S1 (CC), S6 and S7 (CC) appear to be slightly farther from the rest (Fig. 8).

The combustion features identified in the "Lower" subunit are mainly distributed in the central-western part of the cave, forming what appears to be two distinct groups separated by a maximum distance of 1.35 m (Fig. 8). The northern group

(GF1) includes features S24 (eph.), S16, S21, S22, S23, S18, and S41. All are identified as combustion features or lenses, ranging from 1 to 3 cm thick, except for S21 and S18 that are flatter and thicker (6–7 cm and 5 cm thick, respectively). S22 is bioturbated, and S41 shows post-depositional alteration. Feature S21 consists of two different combustion features, with six sublayers and charcoal fragments up to 2 cm in size (Marcazzan et al., 2023). S18 is flat (5 cm thick) and has three sublayers that can be traced and plotted independently (SI3, Fig. S16). The description of this feature indicates that the ash is mixed with carbonated sand (extremely porous), and black coating on the surface, along with fragments of chert and bone altered by heat in the second sublayer (Marcazzan et al., 2023). The clear identification of the sublayers and their individualization, along with the mixture of ashes and sand, and the preservation of burned chert and bone fragments, suggest that this hearth may have been reactivated/reused several times. It is likely that sand was used to extinguish the fire, which would explain the clear differentiation between sublevels and the presence of sterile layers that help their identification. Sand is a well-known fire extinguisher by absorbing heat and smothering the oxygen supply (Yao et al., 2021), making it especially efficient for small fires in protected or sheltered areas, as well as slow-burning outdoor hearths, such those used for cooking.

On the other hand, S41, parallel to S18, is identified as a combustion feature related to a charcoal accumulation and post-depositional alteration (Marcazzan et al., 2023). It may correspond to an adjacent feature to S18, which could have been used simultaneously (Clark & Ranlett, 2022; White et al., 2017). However, since there is evidence for the presence of carnivores at Grotta di Fumane albeit as ephemeral visitors (Romandini et al., 2014), S41 might actually be the result of carnivore activity, and therefore a feature derived from S18. Carnivores can alter hearths and create secondary accumulations of charcoal and ashes that might be mistaken for anthropogenic features (Camarós et al., 2013). The position of these features near the cave entrance could have attracted the animals, who then altered them. This aligns with the observation that S18 seems to be a more controlled feature, with several events indicating a possible reuse/reactivation, while S41, parallel to S18, shows charcoal accumulation and evidence of post-depositional alteration.

The southern group of features (GF2) includes S45, S47 (CC), S48, S44, and S40, which differ in characteristics from those in GF1. All of these features are lens-type features, except for S44, which is flat and 9–10 cm thick. As observed in GF1, flat combustion features are thicker than the lens-type ones. S45 is the largest of these, divided into two parts: one dark layer rich in organic matter and charcoal and a rubified layer at the bottom. Like S44, this feature shows post-depositional alteration. S40 is bioturbated (Marcazzan et al., 2023), and except for S47, which is a charcoal concentration (CC), all features in this group show evidence of post-depositional alteration or bioturbation.

Between these two groups, about 1 m from the wall, there are two features: S15 and S25 (Fig. 8). S15 was not identified as a combustion feature, nor as an accumulation of combustion residues or charcoal accumulation (Marcazzan et al., 2023). However, two areas are identified: one with angular eboulis, large charcoals and slight bioturbation, and another with the same brown color but some stones with darker coatings (Marcazzan et al., 2023). S25, identified as a combustion feature, is approximately 5 cm thick and consists of two sublayers: one very dark grayish-brown, rich in charcoal and organic matter, and another reddish layer. Post-depositional events and irregular microstratigraphy have been identified (Marcazzan et al., 2023).

The features that could not be classified by subunits are: S33, S35, S46, S26, S2, S4, S19, and S20. These features are either too far from the others, some even outside the limits of the rockshelter that could not be correlated with the rest of the features or they lack sufficient remains to provide meaningful or conclusive archaeostratigraphic results.

Spatial Distribution of Artifacts by Subunits

The archaeostratigraphic analysis has enabled the classification of combustion features by subunits and the identification of several archaeostratigraphic sublevels. As a result, a new map of feature distribution, based on these subunits, has been created. Thus, we have attempted to remap the artifact distribution according to the new subunit allocation by assigning the identified concentrations to their corresponding subunit. This was done for the concentrations that could be clearly attributed to specific subunits, as identified in the archaeostratigraphic sections and described in the results section of this work (Section 3.3). This separation could not be made for the whole assemblage. In some parts, although different sublevels could be distinguished (as can be seen in the archaeostratigraphic sections), it was preferred to be cautious and only apply this separation where it was clearly visible in the accumulations and their relationship to the corresponding features. As expected, as in most of the archaeostratigraphic analysis, this separation was easier to perform in areas with a higher density of remains.

Several concentrations were successfully separated and assigned to their corresponding subunits. Thus, the concentrations initially identified by Govoni (2022) can be attributed to at least two clearly distinguishable events of occupation or activity, rather than a single deposition event. Even the same concentration is "composed" of several different moments in time. The most noticeable differentiation occurs with charcoal, burned stones, and lithics, as bones are quite dispersed throughout the cave (except along the eastern wall, where the main bone accumulation was identified). When comparing the KDE data of the entire A9 charcoal assemblage with the data divided into subunits, it becomes clear that the two main charcoal concentrations correspond to two distinct events, rather than a single one (Fig. 9). The charcoal accumulation to the north, clearly related to a significant accumulation of stones with evidence of direct or indirect thermal alteration, belongs to the "Lower" subunit, while the accumulation located to the south corresponds to the "Upper" subunit (Fig. 9).

The distribution of lithic artifacts shows that one of the main accumulations, located to the south, corresponds to the "Lower" subunit (Fig. 10), while a secondary accumulation, further north, corresponds to the "Upper" subunit (Fig. 10).

Both accumulations are located in western area of the cave, where most of the combustion features are found. It is interesting to highlight that charcoal and lithics

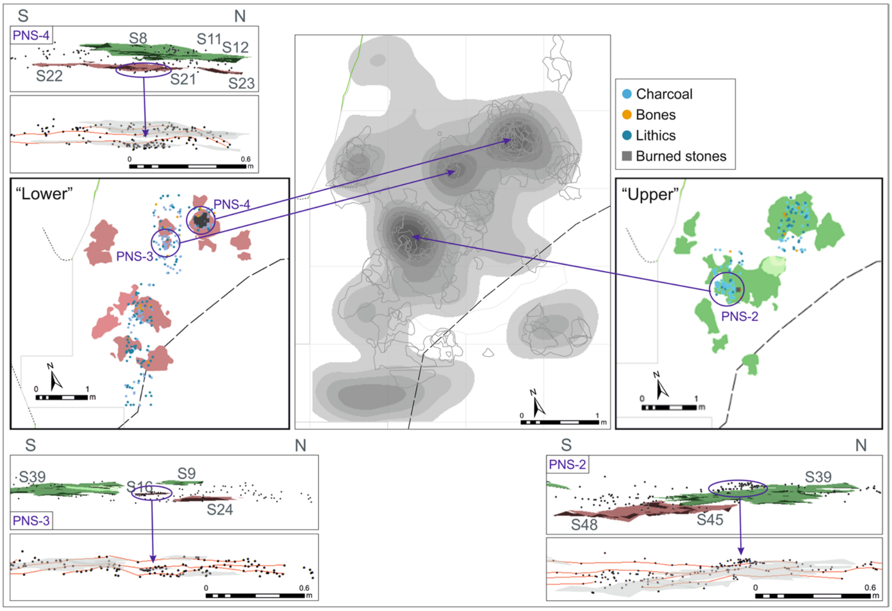

Fig. 9 Identification, individualization, and assignment of some charcoal clusters (and burned stones) to their corresponding sublevel. This figure shows the stretch of interest in the selected archaeostratigraphic sections. For complete information and analysis of the sections, see SI3

do not overlap when separated by subunits. In the case of the "Lower" subunit, the charcoal accumulation is located to the north, while the lithic accumulation is to the south (Figs. 9 and 10). In contrast, the "Upper" subunit shows the reverse pattern, with the highest charcoal accumulation to the south and the lithic accumulation to the north (Figs. 9 and 10).

This distinct distribution pattern of remains, which appear to be associated with different activities, aligns with the groups of features identified for the "Lower" subunit, suggesting a differential use or different activities between these two groups of features. The main accumulation of lithics distinguishable by sublevel—while the rest of concentrations consists of charcoal or burned stones—is associated with feature S44 and comprises 20 pieces made from the same raw material. This accumulation includes one refitted core, eight cortical flakes, and two hinged pseudo-Levallois points, with the remaining elements being reparatory products, overshot flakes ($n = 3$) and core-management flakes (Delpiano et al., 2019b). This highly localized concentration, near one of the combustion features and away from the area where a major charcoal concentration is found, seems to indicate simultaneity in the activities (Delpiano et al., 2019b). This set is completely refitted, indicating that first-choice products were removed and used elsewhere, while the accumulated elements represent a secondary discharge after knapping activity (Delpiano & Peresani, 2017; Delpiano et al., 2019b).

The spatial organization seen in Grotta di Fumane reflects patterns similar to those observed at other sites of similar chronology. In unit SU13 of Oscurusciuto

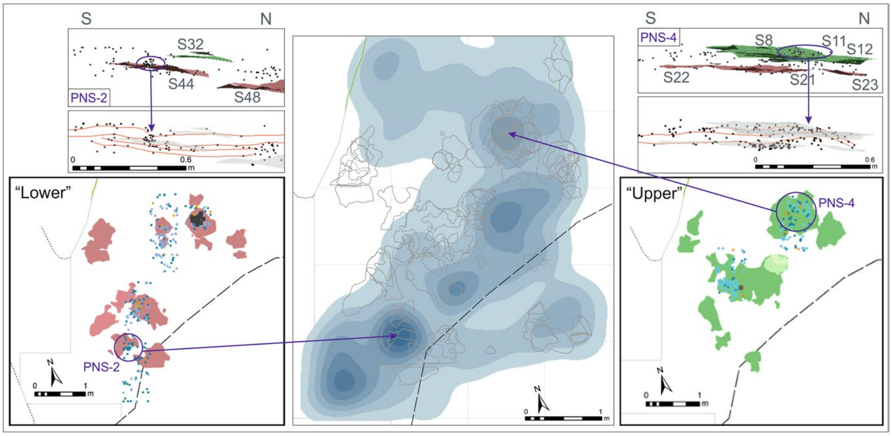

Fig. 10 Identification, individualization, and assignment of some lithic clusters to their corresponding sublevel. This figure shows the stretch of interest in the selected archaeostratigraphic sections. For complete information and analysis of the sections see SI3

rockshelter, eight small hearths were identified, where only three of which were superimposed and aligned parallel to the rockshelter wall, dividing the settlement area between inner and outer parts (Spagnolo et al., 2019). The inner area, between the hearths and the wall, contains fewer artifacts and it was interpreted as a resting/sleeping area. In contrast, the outer area, associated with the combustion features, has a higher concentration of artifacts, and it was interpreted as a multipurpose activity area (Spagnolo et al., 2019). In unit SU11 of the same site, a continuity in space use and settlement dynamics was observed, although this unit was interpreted as a long-term palimpsest, while SU13 as a short-term palimpsest. SU11 contains a great variety of hearths and differences in their distribution (Spagnolo et al., 2020a). Similar to Unit A9 at Grotta di Fumane, Spagnolo et al. (2020a) identified two subunits in SU11, with variances in the combustion features. These features and their associated remains were separated into subunits, resulting in a spatial partition of the shelter into "inner place" and "outer place" (Spagnolo et al., 2020a). Abric Romaní is the paradigm of spatial archaeology studies associated with Neanderthals, with well-preserved successive levels evidencing a repeated use of space over time. The use and organization of the space includes hearth-related accumulations (Vaquero et al., 2017) where knapping and fauna processing activities occurred, with refitting sequences suggesting mobility between these hearth-related accumulations interpreted as multifunctional areas (Vaquero & Pastó, 2001). In addition, there is evidence of resting areas and the use of shelter elements, such as blocks, to position and protect the hearths (Bargalló, et al., 2020; Vallverdú et al., 2010). Similarly, in layer 56 at Molare rockshelter, although several sublayers were identified within the same unit, patterns of behavior suggest a similar use of space in each of these occupation events, in particular the placement and separation between lithic production areas and lithic tool use areas (Spagnolo et al., 2020b). This organization has been interpreted as hearth-related activity areas, more specifically a spatial-functional specialization (Spagnolo et al., 2020b).

The observations made at Molare rockshelter are similar to those at Grotta di Fumane, where spaces were repeatedly reused for specific tasks in each subunit. In general terms, the largest accumulations of lithics and bones are observed in the same area of the cave, particularly in the eastern area of the cave, where large accumulations cannot be further subdivided by subunits. On the other hand, the central-western area shows a repeated use of space, evidenced by the high number of superimposed hearths. However, although there is evidence of a repeated use of the same areas across the two subunits, some differences in activity organization have been observed, particularly in the distribution of lithic and charcoal accumulations between the "Lower" and "Upper" subunits of A9.

In addition, in Unit A9 there is a clear relationship between bone retouchers and retouched lithic tools, as well as in the case of burned elements. The retouched lithics are associated not only with bones used as retouchers but also with some combustion features located in the outer part of the cave. The relationship between burned lithics and burned bones is even more evident, as they coincide in practically all cases. This raises two possible scenarios or possibilities in the interpretation of these spaces. First, the eastern part of the site may have served as a processing area, where fauna exploitation activities took part and where lithics were used for butchery alongside with some bones used as retouchers for reshaping or rejuvenating lithic tools. According to this, the burned remains found on the opposite side could correspond to remains processed and discarded after consumption, left around the combustion areas that would have acted as centralizing elements of activities (Binford, 1978a, 1983). The other scenario is that the eastern area functioned as a secondary disposal area, where discarded remains were accumulated over time at the periphery of the main activity area (Binford, 1983). This would also coincide with the number of bone refits found in this area (Modolo et al., 2025). In this case, the central-western area would be linked to specific activities, resulting in smaller, and more discrete accumulations, such as those that have been identified by archaeostratigraphy, which are related to the combustion features. This structuring of the space with well-defined areas and organized activities seems to point to a domestic use of the cave rather than a use dedicated exclusively to the exploitation of resources. In this latter case, it would not be possible to observe any type of structuring of the space, with main areas and discard zones, but rather evidence of intensive use of the space and zones differentiated by the type of resources exploited (Sánchez-Romero et al., 2024).

The main limitation at Grotta di Fumane, as in most Paleolithic sites, is that it is a palimpsest. In this case, not only "vertical" but also a "horizontal" palimpsest, where several events and patterns have been identified and described. While some accumulations can be individualized and assigned to subunits, this is not the case throughout the site. The central-western area offers high resolution for subunits separation, while the eastern area, where most of the remains are accumulated, is difficult to subdivide into subunits and correlate with the other side of the site for continuity. The lack of a clear separation in the eastern area, combined with the near absence of combustion features at the depressed point where S6 is located, could indicate that this area was likely a discard zone: an area distant from the main area of activity, near to tunnel C and adjacent to the wall. Here, several charcoal concentrations (CC) were identified, but the subunits cannot be separated. Dumping or discard areas are often related to reworking actions, either intentional or unintentional, due to the random and chaotic distribution of elements and the challenges in identifying sublayers (Miller et al., 2010; Mallol et al., 2013; Marcazzan et al., 2023). Feature S6, identified as an isolated concentration of anthropogenic material with minimal anthropogenic input, shows little distinction between feature and non-feature, and its micromorphological analysis lacks proper arrangement (Marcazzan et al., 2023). Similar accumulations of bones and artifacts away from main activity areas have been identified at other sites, including Canalettes rockshelter (France), Amud cave (Israel), Karabi Tambching (Crimea), and Oscurusciuto (Italy) (Meignen, 1993; Alperson-Afil and Hovers, 2005; Anderson & Burke, 2008; Spagnolo et al., 2019; Vaquero, 2022).

Conclusions

Spatial studies are key to understanding the spatial behavior of human groups, especially among hunter-gatherers, where evidence of spatial structuring is less evident. The identification of areas with greater or lesser accumulation of remains, the presence and location of hearths, and the combination of these in the so-called hearth-related assemblages provide important insights to infer the social organization and the activities of these groups, as well as their ability to reuse specific spaces over time.

Unit A9 of Grotta di Fumane shows repeated use of space by Neanderthal groups over time, with a remarkable spatial organization that seems to have been maintained throughout different episodes of occupation. The main lithic and bone accumulations are located in the eastern part of the cave, where combustion features are scarce. In contrast, the center-western part of the cave, where most of the combustion features are located, shows more discrete accumulations linked to those features. Although the discrete accumulations differ in activity types (as we observed in the accumulations of charcoal and burned stones, and lithics), the area with the largest accumulation of remains seems to have been used consistently for similar activities. This "memory" in the repeated use of spaces has been evidenced at other Italian sites, such as Molare and Oscurusciuto (Spagnolo et al., 2019, 2020a, 2020b), where occupation events separated into subunits based on hearth positions and archaeostratigraphy have revealed that similar activity and occupation patterns occurred over time. Although it is challenging to determine the exact spatio-temporal range between subunits, recent studies (Herrejón-Lagunilla et al., 2024) have made it possible to infer the spatio-temporal distance between hearths that appear to belong to the same event. These aspects, together with the observations about the location of hearths, whose placement is largely determined by the seasonal temperature differences (both interior and exterior), lead us to suggest that Grotta di Fumane was not only used repeatedly, but may have been visited during the same seasons of the year over an indeterminate period of time. This seasonal use of Grotta di Fumane is also supported by faunal analyses, more specifically dental wear analysis and cementochronology of cervid molars (Livraghi et al., 2025; Romandini et al., 2014), and micromorphology, which points to a phase of reduced percolation of pore water and therefore to a dry and/or warm period during the formation of Unit A9 (Kehl et al., 2025). While the question about timing remains unclear, we have evidence that sufficient time passed between occupation events, as seen in the sedimentation between the "Upper" and "Lower" subunits.

The organization of the space in groups seems evident when we separate the combustion features by subunits, revealing different activities in each case. However, although this type of organization has been observed in groups of modern hunter-gatherers and in other Neanderthal sites, it is important to remark that we are dealing with a palimpsest, meaning that the groups we have identified and "extracted" from a palimpsest, may themselves constitute further palimpsests. This brings us to the type of palimpsests (Bailey, 2007) and that what we find in Unit A9 could be considered two different types or scales of palimpsests. On a larger scale, such as the "Upper" and "Lower" subunits, differentiated through archaeostratigraphy and the analysis of the combustion features, especially those that are superimposed. And on a smaller scale, within these subunits, which we referred to as sublevels. These sublevels have allowed us to identify continuous gaps that enabled us to glimpse shorter, less evident moments in the archaeo-sedimentary record, separating distinct events or moments of activities carried out in the cave. We could even consider a third category, involving horizontal palimpsests, which pose an added difficulty when interpreting the sites. In this sense, it would be very challenging to infer whether it was the same occupation event or a different event in time, but in different areas of the cave. With this scenario, it is almost impossible to estimate questions like the number of individuals that visited and/or occupied the cave. Interesting approaches (Hamilton et al., 2018) observing the variations among individual camps that could be related to the dynamics of the camp area, number of occupants, and residence time cannot be applied in the case of Grotta di Fumane, at least with the current data. This approach is problematic to apply when we are talking about a palimpsest in a space as confined as a cave (Galanidou, 2000), and with evidence that this locality was likely visited seasonally by humans on their way to other locations. Therefore, estimating the number of occupants, although attractive in the sense of trying to pinpoint the complete scene of Grotta di Fumane and its visitors, is incredibly complex when we are dealing with a palimpsest.

Finally, it is important to highlight the functionality of the sites. Neanderthal groups moved according to the availability of resources, with seasonal occupations, as in the case of Grotta di Fumane, or shorter stays for the specific exploitation of resources, such as the hunting stops identified at sites such as Amalda I (Level VII) and Amalda III (Level VI) (Rios-Garaizar, 2012; Sánchez-Romero et al., 2020; Rios-Garaizar et al., 2024). In this sense, it is important to underline that what we find in the archaeological record largely depends on the use of the site and the intensity of the visits, which could vary depending on factors such as the duration of stays, the size of the groups, or the time elapsed between visits. And that during these intervals, the space could have been used by other animals, such as carnivores. There are numerous elements to consider and that are decisive when constructing hypotheses about the modes of occupation and organization of the site by human groups. Thus, it is worth asking whether these possible differences considered between human groups in terms of organization of space are related to cognitive aspects, or rather to the functionality and use of space, the duration of occupation events, post-depositional factors that could have affected the distribution and/or accumulation of artifacts, or the nature and context of the site itself (rockshelter/cave or an open-air site), and its location.

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Declarations

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References

Alperson-Afil, N., & Hovers, E. (2005). Differential use of space in the Neandertal site of Amud cave. *Israel. Eurasian Prehistory, 3*(1), 3–22.

Anderson, K. L., & Burke, A. (2008). Refining the definition of cultural levels at Karabi Tamchin: A quantitative approach to vertical intra-site spatial analysis. *Journal of Archaeological Sciences, 35*, 2274–2285.

Arteaga-Brieba, A., Courtenay, L. A., Cobo-Sánchez, L., Rodríguez-Hidalgo, A., Saladié, P., Ollé, A., & Mosquera, M. (2023). An archaeostratigraphic consideration of the Gran Dolina TD102 cultural sequence from a quantitative approach. *Quaternary Science Reviews, 309*, 108033. https://doi.org/10.1016/j.quascirev.2023.108033

Bailey, G. (2007). Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology, 26*, 198–223.

Bargalló, A., Gabucio, M. J., Gómez de Soler, B., Chacón, M. G., & Vaquero, M. (2020). Rebuilding the daily scenario of Neanderthal settlement. *Journal of Archaeological Science Reports, 29*, 102139.

Binford, L. R. (1978a). *Nunamiut archaeology*. Academic Press.

Binford, L. R. (1978b). Dimensional analysis of behavior and site structure: Learning from an Eskimo hunting stand. *American Antiquity, 43*, 330–361.

Binford, L. R. (1983). *In pursuit of the past: Decoding the archaeological record*. Thames and Hudson.

Camarós, E., Cueto, M., Teira, L. C., Tapia, J., Cubas, M., Blasco, R., Rosell, J., & Rivals, F. (2013). Large carnivores as taphonomic agents of space modifications: An experimental approach with archaeological implications. *Journal of Archaeological Science, 40*, 1361–1368.

Clark, A. E. (2023). Tracking the emergence of an organized use of space: A direct comparison of the spatial patterning within Middle and Upper Paleolithic open-air sites. *Journal of Human Evolution, 185*, 103455. https://doi.org/10.1016/j.jhevol.2023.103455

Clark, A.E. and Ranlett, S. (2022) The origins of a built environment. Placemaking and the spatial signatures of Neanderthals and Modern Humans. In: Macdonald, D. & Andrews, B. (Eds.) More than shelter from the storm: Hunter-gatherer, houses and the built environment. The University of Florida Press. 13–39

Cremaschi, M., Peresani, M., & Pizziolo, G. (2002). Analisi spaziale del suolo d'abitato musteriano BR6base della Grotta di Fumane. In Peretto C. (a cura di). Analisi informatizzata e trattamento dati delle strutture di abitato di età preistorica e protostorica in Italia. Istituto Italiano di Preistoria e Protostoria. *Progetti, 1*, 59–70.

De la Torre, I., & Wehr, K. (2018). Site formation processes of the early Acheulean assemblage at EF-HR (Olduvai Gorge, Tanzania). *Journal of Human Evolution, 120*, 298–328.

Delpiano, D., & Peresani, M. (2017). Exploring Neanderthal skills and lithic economy. The implication of a refitted Discoid reduction sequence reconstructed using 3D virtual analysis. *Comptes Rendus Palevol, 16*(8), 865–877.

Delpiano, D., Heasley, K., & Peresani, M. (2018). Assessing Neanderthal land use and lithic raw material management in Discoid technology. *Journal of Anthropological Sciences, 96*, 89–110. https://doi.org/10.4436/jass.96006

Delpiano, D., Zupancich, A., & Peresani, M. (2019a). Innovative Neanderthals: Results from an integrated analytical approach applied to backed stone tools. *Journal of Archaeological Science, 110*, 105011. https://doi.org/10.1016/j.jas.2019.105011

Delpiano, D., Cocilova, A., Zangrossi, F., & Peresani, M. (2019b). Potentialities of the virtual analysis of lithic refitting: Case studies from the Middle and Upper Paleolithic. *Archaeological and Anthropological Sciences, 11*, 4467–4489. https://doi.org/10.1007/s12520-019-00779-7

Fiore, I., Gala, M., Romandini, M., Cocca, E., Tagliacozzo, A., & Peresani, M. (2016). From feathers to food: Reconstructing the complete exploitation of avifaunal resources by Neanderthals at Fumane cave, unit A9. *Quaternary International, 421*, 134–153.

Gabucio, M. J., Fernández-Laso, M. C., & Rosell, J. (2017). Turning a rock shelter into a home. Neanderthal use of space in Abric Romaní levels M and O. *Historical Biology, 30*(6), 743–766. https://doi.org/10.1080/08912963.2017.1340470

Gabucio, M.J., Bargalló, A., Saladié, P., Romagnoli, F., Chacón, M. G., Vallverdú, J. and Vaquero, M. (2023). Using GIS and geostatistical techniques to identify Neanderthal campsites at archaeolevel Ob at Abric Romaní. Archaeological and Anthropological Sciences 15(24), https://doi.org/10.1007/s12520-023-01715-6

Galanidou, N. (2000). Patterns in caves: Foragers, horticulturists, and the use of space. *Journal of Anthropological Archaeology, 29*, 243–275.

Getis, A. (1964). Temporal land-use pattern analysis with the use of nearest neighbor and quadrat methods. *Annals of the Association of American Geographers, 54*(3), 391–399.

Getis, A., & Ord, J. K. (1992). The analysis of spatial association by use of distance statistics. *Geographical Analysis, 24*, 189–206.

Giusti, D., Tourloukis, V., Konidaris, G. E., Thompson, N., Karkanas, P., Panagopoulou, E., & Harvati, K. (2018). Beyond maps: Patterns of formation processes at the Middle Pleistocene open-air site of Marathousa 1. *Megalopolis Basin, Greece, Quaternary International, 497*, 137–153.

Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., & Wadley, L. (2009). Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu Cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences, 1*, 95–122. https://doi.org/10.1007/s12520-009-0008-1

Goldberg, P., Dibble, H., Berna, F., Sandgathe, D., McPherron, S. J. P., & Turq, A. (2012). New evidence on Neanderthal use of fire: Examples from Roc de Marsal and Pech de l'Azé IV. *Quaternary International, 247*, 325–340.

Govoni, M. (2022). Il livello musteriano A9 di Grotta di Fumane (VR): Analisi dell'occupazione neandertaliana tramite la distribuzione spaziale dei reperti. MA thesis. Università degli Studi di Ferrara

Hamilton, M. J., Buchanan, B., & Walker, R. S. (2018). Scaling the size, structure, and dynamics of residentially mobile hunter-gatherer camps. *American Antiquity, 83*(4), 701–720. https://doi.org/10.1017/aaq.2018.39

Herrejón-Lagunilla, A., Villalaín, J. J., Pavón-Carrasco, F. J., Serrano Sánchez-Bravo, M., Sossa-Ríos, S., Mayor, A., Galván, B., Hernández, C. M., Mallol, C., & Carrancho, A. (2024). The time between Palaeolithic hearths. *Nature, 630*, 666–670. https://doi.org/10.1038/s41586-024-07467-0

Higham, T., Brock, F., Peresani, M., Broglio, A., Wood, R., & Douka, K. (2009). Problems with radiocarbon dating the Middle to Upper Palaeolithic. *Quaternary Science Reviews, 28*, 1257–1267.

Higham, T., Douka, K., Wood, R., Ramsey, C. B., Brock, F., et al. (2014). The timing and spatiotemporal patterning of Neanderthal disappearance. *Nature, 512*, 306–309. https://doi.org/10.1038/nature13621

Kedar, Y., & Barkai, R. (2019). The significance of air circulation and hearth location at Paleolithic cave sites. *Open Quaternary, 5*(4), 1–12. https://doi.org/10.5334/oq.52

Kedar, Y., Kedar, G., & Barkai, R. (2020). Setting fire in a Paleolithic cave: The influence of cave dimensions on smoke dispersal. *Journal of Archaeological Science: Reports, 29*, 102112.

Kedar, Y., Kedar, G., Kadowaki, S., & Barkai, R. (2024). Hearth management at a middle Paleolithic rock shelter site: Smoke density analysis at Tor Faraj. *Jordan. Journal of Archaeological Science, 172*, 106107.

Kehl, M., Marcazzan, D., Miller, C. E., Falcucci, A., Duches, R., & Peresani, M. (2025). The upper sedimentary sequence of Grotta di Fumane, Northern Italy: A micromorphological approach to study imprints of human occupation and paleoclimate change. *Geoarchaeology, 40*(2), e70000. https://doi.org/10.1002/gea.70000

Lemorini, C., Peresani, M., Rossetti, P., Malerba, G. and Giacobini, G. (2003). Techno- morphological and use-wear functional analysis: an integrated approach to the study of a discoid industry. In: Peresani, M. (Ed.), Discoid Lithic Technology. Advances and Implications. British Archaeological Reports, International Series, 1120, 257–275. Oxford

Leroi-Gourhan, A. and Brézillon, M. (1966). L'habitation Magdalénienne No. I de Pincevent près Monterau (Seine-et-Marne). Gallia Préhistoire, tome 9, fascicule 2, 263–385

Leroi-Gourhan, A., Brézillon, M. N., Karlin, C., Julien, M., David, F. and Guilloré, P. (1972). Fouilles de Pincevent. Essai d'analyse ethnographique d'un habitat Magdalénien (la section 36). Gallia préhistoire. Suppléments, supplément 7–1

Livraghi, A., Rivals, F., Marcazzan, D., & Peresani, M. (2025). From teeth to seasons: Integrated analysis on ungulate game applied to two late neanderthals' contexts in the Italian Alps. *Quaternary Science Reviews, 350*, 109160.

Mallol, C., Hernández, C. M., 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. *Quaternary International, 315*(27), 3–15. https://doi.org/10.1016/j.quaint.2013.04.009

Mallol, C., Hernández, C., Mercier, N., Falguères, C., Carrancho, Á., Cabanes, D., Vidal-Matutano, P., Connolly, R., Pérez, L., Mayor, A., Ben Arous, E., & Galván, B. (2019). Fire and brief human occupations in Iberia during MIS 4: Evidence from Abric del Pastor (Alcoy, Spain). *Scientific Reports, 9*, 18281. https://doi.org/10.1038/s41598-019-54305-9

Marcazzan, D., Miller, Ch. E., & Conard, N. J. (2022). Burning, dumping, and site use during the Middle and Upper Palaeolithic at Hohle Fels Cave. *SW Germany. Archaeological and Anthropological Sciences, 14*, 178.

Marcazzan, D., Miller, Ch. E., Ligouis, B., Duches, R., Conard, N. J., & Peresani, M. (2023). Middle and Upper Paleolithic occupations of Fumane Cave (Italy): A geoarchaeological investigation of the anthropogenic features. *Journal of Anthropological Sciences, 100*(B), 1–26.

Martellotta, E. F., Delpiano, D., Govoni, M., Nannini, N., Duches, R., & Peresani, M. (2020). The use of bone retouchers in a Mousterian context of Discoid lithic technology. *Archaeological and Anthropological Sciences, 12*, 228.

Martínez-Moreno, J., Mora, R., & De la Torre, I. (2010). The Middle-to-Upper Palaeolithic transition in Cova Gran (Catalunya, Spain) and the extinction of Neanderthals in Iberian Peninsula. *Journal of Human Evolution, 58*, 211–226. https://doi.org/10.1016/j.jhevol.2009.09.002

Meignen, L., Goldberg, P., Bar-Yosef, O. (2007). The hearths at Kebara Cave and their role in site formation processes. In: Bar-Yosef, O. and Meignen, L. (Eds.) Kebara Cave Mt. Carmel, Israel. The Middle and Upper Paleolithic Archaeology, Part I. American School of Prehistoric Research Bulletin 49. Peabody Museum of Archaeology and Ethnology, Harvard University, Cambridge, 91–122

Meignen, L. (1993). Répartition spatiale des vestiges au sol de l'abri des Canalettes. In: Meignen, L. (Ed.), L'abri des Canalettes. Un habitat moustérien sur les grands Causses (Nant, Aveyron). Fouilles 1980- 1986. CNRS Éditions, Paris, 161–197

Mentzer, S. M. (2014). Microarchaeological approaches to the identification and interpretation of combustion features in prehistoric archaeological sites. *Journal of Archaeological Method and Theory, 21*, 616–668. https://doi.org/10.1007/s10816-012-9163-2

Miller, C. E., Conard, N. J., Goldberg, P., & Berna, F. (2010). Dumping, sweeping and trampling: Experimental micromorphological analysis of anthropogenically modified combustion features. In: The taphonomy of burned organic residues and combustion features in archaeological contexts. Proceedings of the Round Table, Valbonne, May 27–29 2008. *Palethnologie, 2*, 25–37. https://doi.org/10.4000/palethnologie.8197

Modolo, M., Delpiano, D., Martellotta, E. F., & Peresani, M. (2025). Bone refits and implications for the reconstruction of a Late Middle Palaeolithic Context: Unit A9 of Fumane Cave. *Journal of Palaeolithic Archaeology, 8*, 1. https://doi.org/10.1007/s41982-024-00201-2

O'Connell, J. F., Hawkes, K., & Blurton Jones, N. G. (1988a). Hadza hunting, butchering, and bone transport and their archaeological implications. *Journal of Anthropological Research, 44*, 113–161.

O'Connell, J. F., Hawkes, K., & Blurton Jones, N. G. (1988b). Hadza scavenging: Implications for Plio-Pleistocene hominid subsistence. *Current Anthropology, 29*, 356–363.

O'Connell, J. F., Hawker, K., & Blurton-Jones, N. G. (1992). Patterns in the distribution, site structure and assemblage composition of Hadza kill-butchering sites. *Journal of Archaeological Science, 19*, 319–345.

Oliver, M. A. (1990). Kriging: A method of interpolation for geographical information systems. *International Journal of Geographic Information, 4*(4), 313–332.

Peresani, M. (2022). Investigating human evolution from a cave. Late Neanderthals and early sapiens at Grotta di Fumane: Present state and outlook. *Journal of Anthropological Sciences, 100*, 71–107. https://doi.org/10.4436/jass.10016

Peresani, M., Cremaschi, M., Ferraro, F., Falguères, Ch., Bahain, J. J., Gruppioni, G., Sibilia, E., Quarta, G., Calcagnile, L., & Dolo, J. M. (2008). Age of the final middle Palaeolithic and Uluzzian levels at Fumane cave, northern Italy, using ^{14}C, ESR, $^{234}U/^{230}Th$ and thermoluminescence methods. *Journal of Archaeological Science, 35*, 2986–2996.

Peresani, M., Fiore, I., Gala, M., Romandini, M., & Tagliacozzo, A. (2011). Late Neandertals and the intentional removal of feathers as evidenced from bird bone taphonomy at Fumane Cave 44 ky B.P., Italy. *Proceedings of the National Academy of Sciences, 108*(10), 3888–3893. https://doi.org/10.1073/pnas.1016212108

Peresani, M., Chrzavzez, J., Danti, A., De March, M., Duches, R., Gurioli, F., Muratori, S., Romandini, M., Trombino, L., & Tagliacozzo, A. (2011). Fire-places, frequentations and the environmental setting of the final Mousterian at Grotta di Fumane: A report from the 2006–2008 research. *Quartär, 58*, 131–151.

Peresani, M., Vanhaeren, M., Quaggiotto, E., Queffelec, A., & d'Errico, F. (2013). An ochered fossil marine shell from the Mousterian of Fumane Cave Italy. *Plos ONE, 8*(7), e68572. https://doi.org/10.1371/journal.pone.0068572

Peresani, M. (2009). Relazione campagna di scavo anno 2009 in Grotta di Fumane. Università degli studi di Ferrara, Dipartimento di Biologia ed Evoluzione, Sezione di Paleobiologia, Preistoria e Antropologia

Rios-Garaizar, J., Sánchez-Romero, L., Arriolabengoa, M., Benito-Calvo, A., Expósito, I., Del Val, M., Karampaglidis, T., Marín-Arroyo, A. B., Pérez-Garrido, C., Arenas-Sorriqueta, E., Eixea, A., Gómez-Olivencia, A., Agudo-Pérez, L., San Emeterio, A., & Taldea, A. A. (2024). MIS5-MIS3 Neanderthal occupations at Amalda III cave (Northern Iberia Peninsula). *Quaternary Science Reviews, 333*, 108666. https://doi.org/10.1016/j.quascirev.2024.108666

Rios-Garaizar, J. (2012). Industria lítica y sociedad en la Transición del Paleolítico Medio al Superior en torno al Golfo de Bizkaia. PUbliCan-Ediciones de la Universidad de Cantabria

Ripley, B. D. (1976). The second-order analysis of stationary point processes. *Journal of Applied Probability, 13*, 255–266.

Romandini, M., Nannini, N., Tagliacozzo, A., & Peresani, M. (2014). The ungulate assemblage from layer A9 at Grotta di Fumane, Italy: A zooarchaeological contribution to the reconstruction of Neanderthal ecology. *Quaternary International, 337*, 11–27.

Romandini, M., Fiore, I., Gala, M., Cestari, M., Guida, G., Tagliacozzo, A., & Peresani, M. (2016). Neanderthal scraping and manual handling of raptors wing bones: Evidence from Fumane Cave. *Experimental Activities and Comparison. Quaternary International, 421*, 154–172. https://doi.org/10.1016/j.quaint.2015.12.078

Sánchez-Romero, L., Benito-Calvo, A., Marín-Arroyo, A. B., Agudo-Pérez, L., Karampaglidis, T., & Rios-Garaizar, J. (2020). New insights for understanding spatial patterning and formation processes of the Neanderthal occupation in the Amalda I cave (Gipuzkoa, Spain). *Nature Scientific Reports, 10*, 8733. https://doi.org/10.1038/s41598-020-65364-8

Sánchez-Romero, L., Benito-Calvo, A., & Rios-Garaizar, J. (2022). Defining and characterising clusters in Palaeolithic sites: A review of methods and constraints. *Journal of Archaeological Method and Theory, 29*, 305–333.

Sánchez-Romero, L., Benito-Calvo, A., De Loecker, D., & Pope, M. (2023). Spatial analysis and site formation processes associated with the Middle Pleistocene hominid teeth from Q1/B waterhole, Boxgrove (West Sussex, UK). *Archaeological and Anthropological Sciences, 15*, 98. https://doi.org/10.1007/s12520-023-01790-9

Sánchez-Romero, L., Martínez-Moreno, J., Benito-Calvo, A., Sánchez-Martínez, J. and Mora Torcal, R. (2024). Not only domestic space: Dismantling short-term occupations in Level 497D of Cova Gran de Santa Linya (Pre-Pyrenees, Spain). Journal of Quaternary Science 1–20, https://doi.org/10.1002/jqs.3648

Sánchez-Romero, L. (2019). Desarrollo y aplicación metodológica para el análisis espacial de yacimientos paleolíticos al aire libre y en cueva. PhD Dissertation. University of Burgos

Siabato, W., & Guzmán-Manrique, J. (2019). La autocorrelación espacial y el desarrollo de la geografía cuantitativa. Cuadernos de geografía. *Revista colombiana de Geografía, 28*(1), 1–22. https://doi.org/10.15446/rcdg.v28n1.76919

Spagnolo, V., Marciani, G., Aureli, D., Berna, F., Toniello, G., Astudillo, F., Boschin, F., Boschato, P., & Ronchitelli, A. (2019). Neanderthal activity and resting areas from stratigraphic unit 13 at the Middle Palaeolithic site of Oscurusciuto (Ginosa – Taranto, Southern Italy). *Quaternary Science Reviews, 217*, 169–193. https://doi.org/10.1016/j.quascirev.2018.06.024

Spagnolo, V., Marciani, G., Aureli, D., Martini, I., Boschato, P., Boschin, F., & Ronchitelli, A. (2020). Climbing the time to see Neanderthal behaviour's continuity and discontinuity: SU11 of the Oscurusciuto Rockshelter (Ginosa, Southern Italy). *Archaeological and Anthropological Sciences, 12*, 54. https://doi.org/10.1007/s12520-019-00971-9

Spagnolo, V., Aureli, D., Martini, I., Ekberg, I., Boschin, F., Crezzini, J., Poggi, G., Boscato, P., & Ronchitelli, A. (2020). Short and close in time: Overlapped occupation from the layer 56 of the Molare Rock shelter (south Italy). *Archaeological and Anthropological Sciences, 12*, 92. https://doi.org/10.1007/s12520-020-01037-x

Terlato, G., Livraghi, A., Romandini, M., & Peresani, M. (2019). Large bovids on Neanderthal menu: Exploitation of Bison priscus and Bos primigenius in northeastern Italy. *Journal of Archaeological Science: Reports, 25*, 129–143. https://doi.org/10.1016/j.jasrep.2019.04.006

Vallverdú, J., Vaquero, M., Cáceres, I., Allué, E., Rosell, J., Saladié, P., Chacón, G., Ollé, A., Canals, A., Sala, R., Courty, M. A., & Carbonell, E. (2010). Sleeping activity area within the site structure of archaic human groups: Evidence from Abric Romaní level N combustion activity areas. *Current Anthropology, 51*(1), 137–145.

Vallverdú, J., Alonso, S., Bargalló, A., Bartrolí, R., Campeny, G., Carrancho, A., Expósito, I., Fontanals, M., Gabucio, J., Gómez, B., Prats, J. M., Sañudo, P., Solé, A., Vilalta, J., & Carbonell, E. (2012).

Combustion structures of archaeological level O and mousterian activity areas with use of fire at the Abric Romaní rockshelter (NE Iberian Peninsula). *Quaternary International, 247*, 313–324.
Vaquero, M., & Pastó, I. (2001). The definition of spatial units in Middle Palaeolithic sites: The hearth-related assemblages. *Journal of Archaeological Sciences, 28*, 1209–1220. https://doi.org/10.1006/jasc.2001.0656
Vaquero, M., Fernández-Laso, M. C., Chacón, M. G., Romagnoli, F., Rosell, J., & Sañudo, P. (2017). Moving things: Comparing lithic and bone refits from a Middle Paleolithic site. *Journal of Anthropological Archaeology, 48*, 262–280.
Vaquero, M. (2022). Chapter 11 – The organisation of living spaces in Neanderthal campsites. In Romagnoli, F., Rivals, F., Benazzi, S. (eds.). Updating Neanderthals. Understanding behavioral complexity in the Late Middle Palaeolithic, 207–225. Academic Press, https://doi.org/10.1016/B978-0-12-821428-2.00001-9
White, R., Mensan, R., Clark, A. E., Tartar, E., Marquer, L., Bourrillon, R., Goldberg, P., Chiotti, L., Cretin, C., Rendu, W., Pike-Tay, A., & Ranlett, S. (2017). Technologies for the control of heat and light in the Vézère Valley Aurignacian. *Current Anthropology, 58*(S16), S288–S302.
Yao, B., Zhu, G., Guo, W., Chen, F., Wang, Z., & Xu, X. (2021). Experimental study of the effectiveness of sands on extinguishing pool fires based on small sand-throwing equipment. *Case Studies in Thermal Engineering, 28*, 101408.
Yellen, J. E. (1977). *Archaeological approaches to the present*. Academic Press.
Zilio, L., Hammond, H., Karampaglidis, T., Sánchez-Romero, L., Blasco, R., Rivals, F., Rufà, A., Picin, A., Chacón, M. G., Demuro, M., Arnold, L. J., & Rosell, J. (2021). Examining Neanderthal and carnivore occupations of Teixonere cave (Moià, Barcelona, Spain) using archaeostratigraphic and intra-site spatial analysis. *Nature Scientific Reports, 11*, 4339. https://doi.org/10.1038/s41598-021-83741-9

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