

Tectonic collapse and the geological masking of Paleolithic human occupations at Gruta da Companheira (southern Portugal)

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Abstract

Gruta da Companheira is a recently discovered cave site in the Algarve (southern Portugal), a region poor in Paleolithic karstic sites and shaped by profoundly transformative geological processes, including tectonics. Here, we present a multi-scalar dataset that integrates macro and microstratigraphy, excavation results, and Spatial Statistical Point Pattern Analysis (SPPA) to reconstruct the processes that led to the accumulation and deep burial of the archaeological sequence exposed to date.

Excavation data show that a normal fault crosses Gruta da Companheira, separating the newly discovered Chamber 3 from northwestern passages. Influenced by seismotectonic activity along larger tectonic structures, recurrent slip movements caused the collapse of roofed passages north-west from Chamber 3, likely blocking a yet unconfirmed hillside entrance. Multiphase sigmoidal veins and fault-related breccias support the hypothesis that this collapse and subsequent infilling were triggered by extensional movements. The limestone blocks deriving from the seismotectonic collapse rolled into Chamber 3, amidst which a mix of archaeological and carnivore activity remains was found. Relative contributions of carnivores and hominins to the primary bone accumulation remain to be fully quantified. Before complete sealing, Chamber 3 was directly connected with the external environments through a narrow subvertical passage, opened by the partial cave collapse. These settings favored the movement of vadose water into the northern area of this chamber, where lithic artifacts, bones, and sediments became extensively cemented by secondary carbonates.

Our study highlights the impacts of major regional geological processes on the formation and deep burial of cave sites in southern Portugal. The model concerns the upper Chamber 3 sequence, which remains under excavation, with less reworked deposits likely below. Critically, the seismotectonic sealing that renders such sites invisible may also shelter them from later erosion, suggesting the Paleolithic record of the region is both richer and better preserved than currently visible.

1. Introduction

Paleolithic cave sites with preserved, stratified sequences are exceptionally scarce in southwesternmost Iberia, particularly in the Algarve region of southern Portugal [1–4]. This scarcity contrasts sharply with the abundant and well-documented cave records of northern, eastern, and central Iberia, where sites such as Atapuerca, El Castillo, El Sidrón, Abric Romani, Bolomor, Gruta da Oliveira, and the Pinilla del Valle complex have provided fundamental evidence for hominin evolution and settlement dynamics throughout the Pleistocene [5–28]. The disparity is especially striking given the Algarve's strategic position at the Atlantic–Mediterranean interface and its access to diverse terrestrial and coastal resources, conditions that would have favored recurrent human occupation during the Pleistocene [4, 29–32]. This ecological contradiction suggests that the regional scarcity of Paleolithic caves may reflect preservation and visibility biases rather than low population densities.

Evidence for Paleolithic occupation in the Algarve is not absent, but rather unevenly preserved and frequently difficult to contextualize. Open-air assemblages documented on Miocene-aged plateaus and fluvial terraces demonstrate recurrent human land use throughout the Pleistocene [3, 4, 33–35]. However, many of these occurrences consist of surface scatters or heavily deflated deposits with limited temporal resolution. While the prominent open-air site of Vale Boi documents sustained Upper Paleolithic occupation of the southwestern coast [36–41], Pleistocene cave evidence remains exceptionally limited. Until recently, this record was represented exclusively by Gruta de Ibn Ammar, where Middle Paleolithic lithics were recovered from cemented deposits that exemplify the complex taphonomic histories characteristic of Algarve karst systems [3, 4, 34, 35, 42].

This scarcity of stratified cave deposits has long been linked to the active geological evolution of the region. As early as 1942 [43] researchers proposed that the interplay of tectonic activity, massive roof collapse, and extensive brecciation might have fundamentally shaped Pleistocene archaeological deposits. Subsequent speleo-archaeological research reinforces this interpretation, suggesting that many potential Paleolithic cave archives may have been destroyed, deeply buried, or rendered inaccessible through the combined effects of karstification, structural collapse, and geological sealing [44]. Original anthropogenic accumulations may have been displaced into deeper endokarstic conduits or preserved only as suspended brecciated remnants adhering to cave walls [1, 2, 45–47]. Ultimately, these intense seismotectonic dynamics act as a powerful geological masking agent, obscuring a potentially rich Paleolithic landscape.

Within this context, the recently identified Gruta da Companheira presents a rare opportunity to bypass this taphonomic filter. Located approximately 2 km east of Ibn Ammar (Fig. 1a), and discovered accidentally during public construction works, the site comprises a system of interconnected chambers hosting deep sedimentary deposits. Ongoing excavations have revealed a well-preserved lithic assemblage technologically consistent with the Middle Paleolithic, together with abundant faunal remains [44, 47, 48]. Its complete concealment beneath the modern surface exemplifies how effectively geological masking can obscure Paleolithic cave sites.

This study aims to establish a high-resolution site formation model detailing the collapse, sealing, and deposition of the topmost layers of Chamber 3 of Gruta da Companheira. To disentangle the anthropogenic signals from the intense geological overprinting, we apply a multiscale approach integrating sediment micromorphology and Spatial Point Pattern Analysis (SPPA). Building on successful frameworks used to dissect palimpsests at other Paleolithic sites [15, 16, 49, 50], this integrated approach provides a high-resolution case study for the Algarve, where comparable stratified cave contexts remain extremely rare. By decoding the mechanisms responsible for the preservation and concealment of Companheira, this study establishes a predictive framework for understanding, and potentially overcoming, the scarcity of Paleolithic cave archives in southwesternmost Iberia.

2. The site

Gruta da Companheira is a dolomitic karst system located on a 20 m-high hill near the Arade River in Portimão, southern Portugal (Fig. 1a). The cavity is hosted within the Middle Jurassic Almádena formation [51, 52].

The site is located within the Algarve Basin, a region highly susceptible to tectonic and seismic activity positioned near the African-Eurasian plate boundary [53]. This region is dominated by the N-S trending Portimão Fault and the E-W Espiche-Odiáxere system, which define local fracturing and drive speleogenesis [53]. Within this context, regional seismic instability is known to trigger large-scale rockfalls and potentially cave collapses [36, 44]. Furthermore, the regional hydrogeology is governed by a network of E-W faults and flexures, such as the Flexura de Algibre, which hydraulically segment the terrain into distinct aquifer blocks [44]. The major Querença-Silves aquifer feeds the nearby Ibn Ammar karstic springs, providing the overarching hydrological context for the Companheira system. The possibility that tectonic structures might have influenced the formation (and collapse) of this cave is further supported by published cartographic data [51], which show that the hill hosting the site is crossed by a 500 m long and east-west trending fault of unknown style (Fig. 1a).

The site was initially identified in the 1980s during road construction, when the cave was breached through two northern openings. Subsequent investigations [44, 47] revealed a complex internal geometry, with a subvertical passage recently unblocked from a debris cone, connecting the hilltop with Chamber 3 and the deeper Chambers 1 and 2 (Fig. 1b-c).

2.1. Archaeological excavations

The investigation of the Companheira system began in 2019 with two test pits (1×1×0.5 m) opened in Chambers 1 and 2 (Fig. 1d). While the test unit in Chamber 1 yielded no archaeological finds, the excavation in Chamber 2 exposed a sediment-filled context rich in lithic materials, including Levallois flakes, notches, and a hard-hammer striker [48]. Based on these positive results, the excavation in Chamber 2 was expanded to 4 m² (2×2 m) in 2021, recovering an enlarged assemblage of lithic artifacts, faunal remains, and marine shells. However, the sedimentary matrix, a chaotic mix of calcareous sediments, terra rossa, and angular limestone blocks from roof collapse, suggested a complex formation history. As demonstrated by Barbieri et al. [47], the sequence in Chamber 2 lies at the foot of a loose, active sediment talus filling a steep passage upslope (Fig. 1d). Erosion of this talus is currently active, transporting sediment, fossils, and artifacts downslope. This morphology indicates that the archaeological assemblage was likely not in situ but reworked from higher chambers closer to the hilltop.

Despite this post-depositional disturbance, proteomic analysis of the faunal assemblage identified remains of bovines, deer, rabbits, and ovicaprids [54]. Most notably, this analysis highlighted the presence of two fragments of long bones belonging to either humans or non-human primates. Further DNA analysis is required to determine the precise taxonomic affinity of these remains. If confirmed as human, they would represent the first such discovery in southern Portugal; conversely, a non-human primate attribution would offer a unique window into Paleolithic ecological interactions [47].

To resolve the stratigraphic source of these materials and investigate the potential for a hilltop access point, a geophysical survey combining Electrical Resistivity Tomography (ERT) and Ground-Penetrating Radar (GPR) was conducted by Barbieri et al. [47]. Their data identified a sub-vertical anomaly on the hilltop plateau, interpreted as a potential access to the system. Guided by these results, our team initiated excavations at the hilltop in 2024. The excavation at the exterior sector covered an area of 40 m², exposing a sub-vertical passage that connects to the lower system at a depth of 3 m (Fig. 1b-d).

Crucially, at approximately 5 m depth, the team identified the entrance (partially filled by a debris cone) to a previously unknown cavity, designated Chamber 3. The cavity contains layered deposits composed of allochthonous terra rossa and limestone rubble. Within these layers, stone tools and faunal remains were recorded. The archaeological excavation conducted inside Chamber 3 covered 7.99 m².

Excavations exposed six stratigraphic sequences available for geoarchaeological assessment (Figs. 1d; 2): the exterior sedimentary profiles named Profile North Outside (PNO) and Profile West Outside (PWO) (Fig. 2a), and the internal deposits of Chamber 3. The latter include the Profile North Inside (PNI) (Fig. 2b), Profile South (PS) and Profile East (PE), which are confined by the cave walls, and the debris cone accumulation in Profile West (PW) (Fig. 2b).

3. Materials and methods

3.1. Excavation strategy and stratigraphy

Hilltop excavation utilized a backhoe loader for surface blocks, followed by manual removal of indurated breccias using electric hammers. Stratigraphic units were excavated by *décapage* and numbered sequentially. All artifacts (> 2 cm) were 3D-recorded (total station, local grid), while clasts > 10 cm were mapped to record orientation. Volumetric control (10 L buckets) was maintained in Chamber 3 and the debris cone (PW) but was unfeasible in the exterior excavation area due to massive block/breccia dominance. All sediment was wet-sieved (4 and 1 mm mesh).

Documentation included LiDAR scanning (iPad Pro/Polycam) and photogrammetry (processed in Agisoft Metashape). Spatial distribution and plotting were performed in R (ggplot2). Stratigraphic profiles were described recording depth, boundary transitions [55], and coarse/fine (c/f) ratios [56]. Fine fractions were assessed for Munsell color and grain size

[57]; gravel attributes included composition, frequency, size (ISO 14688–1:2002), shape [58], roundness [59], and sorting [60].

The data presented in this study derive from the excavation campaigns conducted in 2024 and 2025. As excavations in Chamber 3 are currently ongoing, the quantitative data represents the stratigraphic sequences exposed to date, serving as a geoarchaeological baseline for establishing the site's sealing mechanisms and depositional pathways.

3.2. Micromorphology

The geoarchaeological sampling strategy aimed to cover a representative record of the stratigraphic sequence exposed so far at the site. A total of 7 undisturbed sediment blocks were collected (Fig. 2) from which 16 petrographic thin sections were produced. While the objective was comprehensive coverage, the specific lithological characteristics of the karst deposits imposed certain constraints on sampling continuity.

In the exterior area (PNO; Fig. 2a), the presence of large limestone boulders and the instability of the brecciated fabric prevented sampling of Layers 103, 103A, and 104B. Within Chamber 3 (PNI; Fig. 2b), no sample was collected from Layer 4 because insufficient sediment was available in PS, as it lies against the cave wall. Sampling of Layer 3 was precluded by its extreme cementation and the risk of destabilizing the profile during extraction; however, macroscopic field observations indicate that this unit is stratigraphically analogous to the overlying Layer 2, differing primarily in artifact density (Layer 3 being denser at 0.34 N/L compared to 0.20 N/L for Layer 2) and clast frequency. In PE sampling was restricted due to the minimal sediment depth available against the confining bedrock walls. Similarly, the coarse nature of the debris cone in PW (Fig. 2b) limited sampling as the units were dominated by a mixture of indurated breccias, along with localized loose sediments and clast-supported limestone rubble.

Due to the variable degree of sediment induration, two extraction protocols were employed. Loose sedimentary units were collected using standard plaster of Paris bandaging. Conversely, the strongly cemented and brecciated layers—PNO (Layers 104A, 104C, 104D) and PNI (Layer 2)—required extraction using an electric circular saw.

In the laboratory, samples were oven-dried at 40°C for three days, impregnated with a mixture of polyester resin, styrene, and hardener, and allowed to consolidate in a fume hood for approximately two weeks. Once hardened, the blocks were sectioned into 50 × 75 mm chips and manufactured into 30 µm-thick thin sections. The finished slides were digitized using a flatbed scanner (1200 dpi, reflection mode) and analyzed under a petrographic microscope at magnifications ranging from 5× to 200× using Plane Polarized Light (PPL), Cross-Polarized Light (XPL), and Oblique Incident Light (OIL). Micromorphological descriptions and terminology follow Stoops [60], as well as established criteria in the field [61–66].

3.3. Spatial Statistical Point Pattern Analysis

The SPPA of the archaeological remains in Chamber 3 is used here to describe and quantify the assemblage's spatial structure. This provides independent evidence for post-depositional displacement and diagenesis, complementing the site's micromorphological and stratigraphic data.

Geoarchaeological analysis identified four diagenetically distinct categories of surface coverage on the finds: type A ("cave popcorn") (Fig. 3a-b), type B (calcitic breccia) (Fig. 3c-d), type C (mixed breccia and cave popcorn) (Fig. 3e-f), and uncovered. This analysis addresses three questions (Q1-Q3): (**Q1**) whether cementation categories display a spatial gradient; (**Q2**) whether faunal and lithic remains occupy distinct spatial domains; and (**Q3**) whether bones and lithics exhibit different cementation profiles. Each hypothesis (H1–H3 in S1) is evaluated by comparing observed spatial statistics with simulated expectations under defined null models.

The dataset comprises 1,012 total station-recorded finds (x–y–z coordinates) from Layers 2, 3, 4, and 104E (Layer 1 was excluded as late intrusive). Of these, 871 (86.1%) are faunal remains and 141 (13.9%) are lithics. Although Layer 4 is

currently still under excavation and spatially limited to the southern area of the chamber, its remarkably high find density (0.36 N/L; Table 1) provides a robust sample size that justifies its inclusion in the spatial models. Nevertheless, because the available data represent only a subset of the layer, comparisons with other layers are provisional. The consistency of the observed spatial patterns will be tested as excavation expands to include the currently unexcavated northern sector. Layer 104E represents the NW entrance debris cone, where sediment and clasts entered the chamber and vadose percolation was most intense. The formation model predicts type B breccia to concentrate here (H1a in section S1). Including Layer 104E extends the observation window across the full NW–SE deposit to test the cementation gradient's directionality. We performed both combined and layer-specific analyses. The combined analyses use all layers together to evaluate the overall spatial structure of the assemblage. The layer-specific analyses allow us to assess whether the observed spatial patterns are consistent through time or vary between depositional episodes. Layer 104E is retained in all combined analyses but excluded from per-layer analyses due to its small sample size ($n = 40$) and distinct depositional context.

Given the deposit's diagonal NW–SE structure, results are reported in plain view (xy) and vertical section (xz). The observation window, defined as the convex hull of all finds combined with deposit-layer boundary references, yields a 7.99 m² plan-view area. To allow direct comparison among layers and maintain a consistent analytical framework, all tests were conducted within the same observation window. The incomplete excavation of Layer 4 and the restricted spatial extent of Layer 104E are explicitly considered in the interpretation of the results. In particular, adaptive relative-risk estimates are interpreted cautiously, as their locally varying bandwidths may be influenced by the empty space and may yield less reliable intensity contrasts near the boundary of the excavated layer extent (S2). Analyses were executed in R using the *spatstat* [67] and *sparr* [68] packages. Departure from complete spatial randomness (CSR) was assessed via the Hopkins–Skellam test [69]. Spatial intensity and hotspots were estimated by kernel smoothing and tested using a scan likelihood-ratio statistic [70, 71]. Spatial segregation was quantified using a Monte Carlo test [72] and the nearest-neighbor equality function $\hat{E}(k)$, which measures the probability that the k -th nearest neighbour of a find shares the same category [73]. Bone-lithic spatial association was assessed using the inhomogeneous cross-K function under two null hypotheses (random labelling and independent processes). For Q3, material-cementation association was tested via Pearson chi-square. Per-layer analyses (Layers 2–4) are in Table S1 and Figs S7a–S9b. Code and data are available at the Open Science Framework (OSF) repository (DOI: 10.17605/OSF.IO/2X3VB). For the complete analytical framework, formal hypotheses, and extended spatial plots associated with this methodology, see the Supplementary Information (Figs S1–S9).

4. Results

4.1. Macro and micro stratigraphy

The stratigraphic sequence at Gruta da Companhia is divided into the exterior excavation area (PNO and PWO) and the interior system (Chamber 3), which are physically connected via a conduit exposed during the 2024–2025 excavation campaigns. This vertical passage is structurally controlled by a bedrock fault that, prior to excavation, was almost completely plugged by a steeply dipping debris cone. Excavation of the sub-vertical conduit revealed a central junction providing access to three distinct areas of the cave system. To the East, the system opens into Chamber 3 (Fig. 4a-b). To the North, a passage slopes downward to Chamber 2, exhibiting the *in situ* cave roof and the underlying debris cone that partially plugged the gallery (Fig. 4c). To the West, we documented a gallery obstructed by massive, metric-sized limestone blocks (Fig. 4d). If this passage maintains a horizontal trajectory, it would intersect the break-in-slope between hilltop and western hillside. There, on the ground surface, we observed an accumulation of limestone boulders, possibly indicative of a collapsed entrance (Fig. 1c).

The sedimentary sequence within Chamber 3 is exposed in four distinct profiles: PS, PE, PNI, and PW (Figs. 1d, 2b). The following stratigraphic succession is described from bottom to top as observed across these exposures.

PS is largely defined by the cave wall which marks the southern boundary of the excavation; it is characterized by **Layer 4**, a poorly consolidated sandy terra rossa containing abundant archaeological materials (bones and stone tools). Layer 4 transitions laterally into **Layer 3**, a stratigraphic unit exhibiting significant spatial and textural variability across the excavated area. Near PS, Layer 3 presents as a chaotic mixture of loose sediment, conglomerates, and breccia fragments containing bones and stone tools. PE is delimited by the limestone bedrock wall which constrains the sedimentary sequence. In contrast, the PNI highlights the eastward slope of the stratigraphic layers and exposes the lateral continuation of Layer 3. In this northern exposure, the deposit appears visually and texturally distinct from its southern counterpart, presenting instead as a brecciated terra rossa with angular gravels in a convoluted arrangement (c/f 90/10%) (Fig S10a).

Overlying this is **Layer 2**, an intermediate cemented deposit rich in coarse subangular limestone fragments and few phosphatic carnivore coprolites (Figs. 5a, c; S10 b-d). Microstratigraphically, Layer 2 is characterized by extensive calcite cementation, including isopachous crusts and localized stromatolitic textures (Fig. 5b), that completely occludes porosity and embeds rounded terra rossa aggregates (Fig S10e-f) and reworked breccia fragments (Fig. 5d-f). Furthermore, anthropogenic inclusions within this highly indurated matrix, such as charcoal, burnt, and unburnt bones, frequently exhibit vertical orientations and poor internal preservation due to pervasive calcite infilling (Figs. 5d-g; S10g-i), and incipient tunneling caused by bacterial and fungal activity (Fig S10j) [74, 75]. Additionally, embedded limestone fragments within this unit frequently exhibit cracks and sigmoidal veins filled by terra rossa or calcitic cement (Fig S10k-m). For extended microstratigraphic descriptions, see S4.

The sequence is topped by **Layer 1**, composed of clayish medium-to-coarse gravels (5YR 4/6) with a wavy basal contact. In thin section, Layer 1 displays a matrix-supported, actively bioturbated loose terra rossa (Fig. 5h), reworked breccia fragments with interstitial calcite cement (Fig. 5h), and complex recrystallized carbonate aggregates (Fig. 5i). Crucially, Layer 1 exhibits the same characteristics as the exterior Layer 101, corresponding to loose terra rossa.

Finally, PW, located at the excavated entrance to Chamber 3, exposes the steeply dipping (~ 65°) debris cone that prograde over the chamber's stratified sequence. Composed of large limestone blocks morphologically identical to the exterior Layer 103, this cone descends from the vertical conduit (above Layer 1) down to the base of Layer 3. Importantly, the stratigraphic contact between this debris cone and Layers 3 and 2 is diffuse and difficult to trace, presenting as an interfingered transition zone characterized by distinct boulder orientations. Ultimately, this cone serves as a transition to the basal exterior units, Layers 104D and 104E.

The exterior area exposes a sequence of indurated breccias and blocky deposits filling the bedrock depression shaped by the east-west fault (Fig S11a-b). The sequence begins at the base with **Layer 104E**, a chaotic mixture of breccia fragments and loose sediment at the excavated entrance. This is overlain by Layers 104D through 104A. **Layer 104D** is a matrix-supported, cemented terra rossa with a sandy loam texture, exhibiting intense bioturbation (abundant fecal pellets and mite excrements), and weathered, vertically oriented few bone fragments coated in sparitic calcite (Fig S11c-e).

The overlying units (104C–104A) display a progressive upward increase in coarse, subangular limestone. This sequence marks a structural transition from a clast-supported chaotic breccia with a high degree of rotational misfit in Layer 104C (Fig S11f) to a mosaic breccia in Layer 104A (Figs. 5j; S11h), where clast density increases to 60–75% and fragments exhibit only minor translation [76–80]. Layer 104C is specifically distinguished by an interstitial silty-clay matrix featuring syn-depositional bioturbation features (Fig S11g). Layer 104A exhibits both syn- and post-depositional cementation; here, calcitic cement encases land snail shells (Fig S11h), and micro-layers composed of micrite and microsparite

occlude inter-clast voids (Fig S11i), and coat subrounded terra rossa aggregates (Fig S11j). Notably, some of these aggregates display internal rotational galaxy features (Figs. 5k; S11k) [63, 81, 82]. Finally, as also observed in Layer 2, embedded fossiliferous limestone fragments within these units often exhibit cracks and sigmoidal veins filled by terra rossa or calcitic cement [83, 84] (Figs. 5l).

These breccias are covered by **Layer 103A** (massive V-shaped limestone boulders) and **Layer 103** (chaotic subangular blocks) (Fig S12a). Above this lies **Layer 102**, a localized yellow clay (10YR 7/8) (Fig S12a-c). At the micro-scale (Fig. 5m), Layer 102 is a matrix-supported deposit with a heavily cracked, blocky microstructure and calcitic crystallitic b-fabric (Fig. 5n). Its coarse fraction is rich in subrounded, extensively recrystallized carbonate aggregates dominated by microspar and sparite (Fig. 5o). The sequence is finally capped by **Layer 101**, a massive yellowish-red (5YR 4/6) terra rossa constituting the present-day surface (Fig S12c). Micromorphologically, Layer 101 is an actively bioturbated soil with a granular microstructure, high secondary porosity, fresh roots, mite excrements (Fig S12d-e), a mica-rich silt fraction (Fig S12f), and a lower frequency of carbonate nodules.

4.2. Archaeological assemblage and distribution

The spatial distribution of recovered materials reveals a sharp contrast in find density between the exterior and interior sectors, heavily influenced by the site's geomorphology (Table 1). The exterior sector (Layers 104A–D, 103, 102, 101) is largely devoid of macroscopic archaeological materials. As detailed in Table 1, only the basal **Layer 104E** yielded an assemblage of 13 lithics and 27 faunal remains associated with the brecciated interface.

Table 1
Stratigraphic units identified at Gruta da Companheira

Sector	Unit	Description	Observations	Lithics (n)	Fauna (n)	Excavated Volume (L)	Find Density (N/L)	Micromorphology Sample (MM)
Exterior	104E	Chaotic breccia and loose sediment	Basal interior-exterior unit (Debris cone)	13	27	510	0.08	-
	104D-A	Indurated, matrix and clast-supported breccias	Sealing the bedrock depression	0	0	10*	-	104D (MM5), 104C (MM3), 104A (MM2).
	103A	Bedrock boulders	V-shaped geometry	-	-	-	-	N/A
	103	Chaotic subangular limestone blocks with few interstitial sediment	Local hilltop source	-	-	-	-	N/A
	102	Localized yellow clay (10YR 7/8)	Tongue-like contact	0	0	-	-	MM4
	101	Yellowish red (5YR 4/6) terra rossa.	Modern land surface	0	0	-	-	MM1
Interior	4	Loose sandy terra rossa	Rich in archaeological materials and localized in the south area of Chamber 3	30	241	760	0.36	-
	3	Brecciated terra rossa with transitional mix	Convolutated arrangement: frequent bones covered with breccia	58	396	1,300	0.34	N/A
	2	Brecciated terra rossa	High coarse fraction (80/20%)	40	207	1,210	0.20	MM6
	1	Loose sandy terra rossa	Yellowish red (5YR 4/6)	12	36	390	0.12	MM7

Note: Fauna counts include unique bone and tooth specimens. Two carnivore coprolites were also recovered from Layer 4. Excavated volumes are calculated based on recorded buckets (1 bucket = 10 L).

*Volume for 104D-A corresponds to the specific removal of Layer 104B recorded in the bucket database.

In contrast, the interior sector (Chamber 3) yielded a high density of finds. As illustrated in Fig. 6a, the spatial distribution of these materials is stratigraphically associated with the debris cone, which is visible as a dense

accumulation of geogenic clasts (shown in grey) that overlays the sedimentary sequence. The vertical succession of archaeological layers is visualized in Fig. 6b, showing distinct depositional units. **Layer 4** has so far yielded 241 faunal specimens and 30 lithic artifacts within a loose sandy terra rossa matrix. The underlying **Layer 3** yielded 396 faunal remains and 58 lithics. **Layer 2** yielded 207 faunal remains and 40 lithics, while the uppermost **Layer 1** contained a reduced assemblage of 36 faunal remains and 12 lithics. Standardized volumetric analysis identifies Layer 4 and 3 as the most concentrated units (0.36 N/L, and 0.34 N/L, respectively), Layer 2 (0.20 N/L), and Layer 1 (0.12 N/L).

Preliminary zooarchaeological assessment indicates high taxonomic diversity. The assemblage is dominated by equids, represented by post-cranial elements and complete teeth, alongside remains of various cervid species. The presence of ursids and smaller carnivores indicates the cave was utilized by both hominins and carnivores. Other notable taxa include rhinoceros, as well as tortoise carapace fragments and crab remains. Although no charcoal has been recovered from the sedimentary matrix to date, distinct combustion traces have been identified on some faunal specimens.

Technologically, the lithic assemblage is defined by a diverse raw material spectrum, including quartz, greywacke, dolerite, and various chert types, some of which are distinct from known regional sources [32]. Techno-typological analysis of the artifacts recovered from Chamber 3 confirms the presence of Middle Paleolithic diagnostic artifacts, including the presence of Levallois flakes and cores on chert, greywacke, and dolerite, as well as the manufacture of formal tools, evidenced by a retouched débordant flake. Diagnostic tools from the Upper Paleolithic or later periods were not identified. The artifacts are remarkably well-preserved, exhibiting fresh edges with only minor macroscopic damage. The assemblage includes small chips and knapping debitage, recovered through systematic wet-sieving. A distinctive feature of this assemblage is the presence of elongated pebbles and slabs of greywacke and dolerite, some of which bear bipolar percussion marks consistent with their use as wedges.

4.3. Spatial statistical point pattern analysis

4.3.1. Q1: Spatial distribution of cementation types

Around 85% of the archaeological remains are covered by brecciated sediment (types B and C) and/or popcorn coating (type A). Cementation distribution is: type A ($n = 423$, 41.8%); type B ($n = 261$, 25.8%); type C ($n = 160$, 15.8%); uncovered ($n = 168$, 16.6%). The analysis of the pooled assemblage combining layers 2, 3 and 4 reveals that all four cementation categories spatial distributions depart significantly from CSR in plain view (Hopkins–Skellam: type A $A = 0.094$, type B $A = 0.210$, type C $A = 0.054$, uncovered $A = 0.244$; all $p = 0.001$, Table 2), indicating spatial clustering over uniform distribution.

Kernel-smoothed intensity maps and spatial density lines reveal a structured mosaic distribution of the types of cementation (Figs. 7c-d; S1). Type A (52.1 finds/m²) concentrates in the SE of the excavated area; type B (32.2 finds/m²) predominates in the central-northern and NW sectors; type C (19.7 finds/m²) occupies intermediate zones. Uncovered finds (20.7 finds/m²) form a single, sharply delimited southern concentration, yielding the only significant scan-test hot-spot ($LR = 229.5$, $p = 0.001$; Table 2). The intensity of this hot spot may be accentuated by the current restriction of Layer 4 to the excavated southern sector and will require reassessment as excavation progresses. The cemented categories produce no significant hot-spots (all $p > 0.36$; Fig. 7e), indicating broader distributions rather than focal points.

The categories are strongly segregated. The Monte Carlo test rejects random label exchange ($T = 206.8$, $p = 0.01$; Table 2). The nearest-neighbour equality function $\hat{E}(k)$ function sits substantially above the theoretical expectations and the simulation envelopes across all neighbour orders $k = 1-20$ (observed ≈ 0.43 vs. expected ≈ 0.29 ; Fig. 7h), showing that finds of the same cementation type neighbour each other far more often than would occur by chance, at every scale of proximity.

Adaptive relative-risk surfaces confirm this spatial structure matches the formation model's directional predictions (Fig. 7f). Type B is significantly over-represented in the NW and central-northern sectors (intense vadose percolation via the entrance). Type A is over-represented in the SE interior (condensation/drip-fed precipitation). Type C is over-represented in a central transitional zone (initial NW breccia cementation followed by displacement and SE interior exposure). Uncoated finds appear furthest from active cementation, and are most strongly over-represented relative to type A.

The same general spatial pattern is observed in the layer-specific analyses (Figs. S7a–S8a, S9a), although for Layer 4 it can only be assessed in the currently excavated southern sector. In section view, cementation types remain spatially structured but do not form discrete vertical horizons (Fig. S1; S6). Their depth distributions overlap substantially (Fig. S6B), indicating that all cementation classes occur across similar elevation ranges. Instead, kernel intensity maps reveal localized lateral concentrations (Fig. S6C): Type A predominates in the eastern sector, Type B in the western sector, and Type C occupies intermediate areas. The dominant-type map (Fig. S6D) also suggests that cementation variability reflects localized diagenetic conditions operating across the chamber and not successive depth-dependent cementation phases.

Consequently, post-depositional chamber conditions formed a persistent NW–SE spatial mosaic likely linked to specific water routes and localized cave microclimates.

Table 2

Combined spatial statistics for cementation types (Q1) and material types (Q2) across all layers. A (Hopkins–Skellam): statistic values < 1 indicate clustering relative to complete spatial randomness (nsim = 999). Scan LR: spatial scan likelihood-ratio statistic (nsim = 999). T (Segregation): Diggle–Zheng–Durr Monte Carlo segregation test statistic (nsim = 99), reported in the combined row for each question. —: not applicable.

Question	Category	n	Intensity (finds m ²)	A (Hopkins- Skellam)	p (HS)	Scan LR	p (Scan)	T (Segregation)	p (Seg)
Q1	TYPE_A	423	52.1	0.094	0.001	64.1	0.779	—	—
Q1	TYPE_B	261	32.2	0.21	0.001	66.2	0.361	—	—
Q1	TYPE_C	160	19.7	0.054	0.001	38.1	0.511	—	—
Q1	Uncovered	168	20.7	0.244	0.001	229.5	0.001	—	—
Q1	combined	1012	124.7	0.084	0.001	—	—	206.84	0.01
Q2	BONE	871	107.3	0.075	0.001	65.7	0.688	—	—
Q2	LITHIC	141	17.4	0.319	0.001	41.6	0.238	—	—
Q2	combined	1012	124.7	0.084	0.001	—	—	46.51	0.01

4.3.2. Q2: Spatial distribution of faunal and lithic remains

Faunal remains ($A = 0.075, p = 0.001$) and lithics ($A = 0.319, p = 0.001$) are significantly clustered relative to CSR (Table 2). The higher A-statistic for lithics reflects a looser, more dispersed pattern of aggregation, given their lower abundance and broader scatter across the excavated area (Fig. 8a).

Across the combined assemblage, intensity maps and spatial density lines show faunal remains (107.3 finds/m²) predominating across the observation window, with both faunal and lithic remains largely overlapping and peaking in the central and eastern sectors (Figs. 8b–d; S2). Lithics (17.4 finds/m²) concentrate in the north-eastern area with

secondary southern clusters. Neither yields a significant single-cluster hot-spot (bones: LR = 65.7, $p = 0.688$; lithics: LR = 41.6, $p = 0.238$; Fig. 8e; Table 2), indicating multimodal distributions.

Bone-lithic spatial segregation is significant ($T = 46.5$, $p = 0.01$; Table 2), but weaker than cementation segregation. $\hat{E}(k)$ exceeds expectations by ~ 4 percentage points, compared to ~ 14 for cementation (Fig. 8h). Adaptive relative-risk surfaces show lithics to be relatively over-represented in the northwestern sector and faunal remains in the southeast (a gradient driven by the estimator's known sensitivity to the sparsely excavated margins of the window, rather than by the actual find locations, which instead cluster in the northeast (Layers 2–3) and south (Layer 4; Fig. 9)). However, this pattern is based on only a few lithic finds within an otherwise low-density area and is therefore unlikely to represent a meaningful spatial trend (Fig. 8f).

The same general pattern is observed in Layer 3, whereas Layer 2 shows slightly higher relative densities of lithics in the northeastern sector. This is the only instance in which lithics locally exhibit higher relative densities than faunal remains. Within the excavated southern portion of Layer 4, faunal remains exhibit a more multimodal spatial distribution than lithics (Fig S7b; S8b; S9b).

The analysis of the combined assemblage shows that under the random-labelling null, the observed cross- K function falls within the simulation envelope (Fig. 8g), showing both materials broadly share the same spatial pattern. Under the independent-processes null, the observed cross- K falls slightly below the lower envelope (Fig S4), indicating bones and lithics co-occur less than expected if driven by entirely independent spatial processes. This weak negative association is also supported by the nearest-neighbour equality function (Fig. 8h).

This slight bone–lithic segregation is also observed in the layer-specific analyses (Figs. S8b), with significant but modest segregation detected in Layers 2 (segregation test $p = 0.01$, Table S1) and 3 (nearest-neighbour equality function, Fig. 8b-g). Together, these results show that bones and lithics are not preserved as two separate spatial accumulations in Chamber 3. Their distributions largely overlap, with only a slight tendency for lithics to be relatively more frequent near the cave wall (Fig. 8d). The recurrence of this relationship within individual layers suggests that both material classes experienced broadly similar spatial processes through time, although the spatial analyses alone cannot distinguish between repeated depositional overlap and post-depositional redistribution.

4.3.3. Q3: Cementation type by material type

Bones and lithics share broadly similar cementation profiles when considering the pooled assemblage, although the differences are statistically significant ($\chi^2 = 13.29$, $df = 3$, $p = 0.004$; Fig. 10). The main difference is that a greater proportion of lithics are uncemented (27.0%) than bones (14.9%). Type A is more common on bones (43.1% vs. 34.0%), while types B and C occur in similar proportions (type B: 26.2% vs. 23.4%; type C: 15.8% vs. 15.6%).

This likely reflects spatial patterning rather than material-specific diagenesis. Lithics are more frequent near the cave wall and the southern uncemented zone, while bones dominate the central and eastern sectors. Therefore, coating differences largely result from depositional location.

Taken together, the point-pattern results suggest that the spatial structure of Chamber 3 is mainly the result of post-depositional redistribution and diagenetic zoning, rather than pristine primary deposition. Cementation types are clustered and segregated, and they form a NW–SE mosaic consistent with the predicted gradient: breccia cementation linked to vadose percolation is strongest near the entrance, while popcorn-type calcite is most common in the interior. Bone and lithic distributions show a shared deposit with weak differentiation between types, not perfect mixing. Their distributions largely overlap, and this pattern is consistent across stratigraphic levels, which suggests stable spatial constraints and diagenetic conditions. Layer 4 is a partial exception, with bone–lithic segregation only marginal and

non-significant ($p = 0.07$; Table S1), compared to the significant segregation observed in Layers 2 and 3, a distinction discussed further below. The persistence of the cementation mosaic and the small bone–lithic offset in the upper Layers 2–3 suggests selective redistribution along preferred pathways, together with progressive cementation that helped preserve spatial structure through time.

5. Discussion

5.1. Site formation history and spatial dynamics

The site formation of Gruta da Companheira follows a tripartite sequence: an initial phase of biological and anthropogenic occupation within a still open cave system, followed by catastrophic geological disruption that reworked and buried the sedimentary deposits, and finally, a period of stabilization defined by restricted hydrology and intense diagenesis. Based on the integration of stratigraphic, micromorphological, and spatial analyses, we propose the following sequence of events (Fig. 11), which remains to be further validated by (yet unavailable) geochronological data.

5.1.1. Chamber 3's pre-collapse setting

In contrast to what was proposed by Barbieri et al., [47], we hypothesize that the area we unblocked to access the cave from the hilltop might not have been the original entrance used by carnivores and possibly by hunter-gatherers during the Pleistocene. Excavation in this area revealed northern and southern limestone walls that display slightly refitting morphology and seem to have been wedged apart by extensional tectonic movements, with the northern component acting as a hanging block (Fig. 1b-c). The fault zone between these two limestone walls is filled with sterile breccia exhibiting sigmoidal veins indicative of repeated extensional movements (Fig. 5j-l) [83, 84], while rare archaeological materials and bones are only found in the breccia layers located at depths comparable to Chamber 3 (ca. 5 m). Together, these observations suggest that there was a time during the Pleistocene, prior to tectonic disruption, when the two limestone walls might have been joined, making this a roofed area of the cave (Figs. 1b-c; 11a).

Our open-air excavation showed that the breccia layers cover a large debris cone that slopes into Chamber 3, towards east, into Chamber 2, towards north, and towards a northwestern passage that has remained unexplored because plugged by limestone blocks (Figs. 4; S12b). Unlike Chamber 3, this passage was not identified by previous electrical resistivity tomography, probably because it is filled with limestone rubble, which exhibits resistivity comparable to the surrounding limestone bedrock [47]. Ground-penetrating radar survey, however, detected reflectors indicative of a small air-filled cavity in an area comparable with the blocked northwestern passage exposed during excavation [47]. This passage might continue for some 10 m towards west, reaching the break-in-slope that separates hilltop from hillside, where we observed a distinct accumulation of metric limestone blocks (Fig. 1c). Future excavations targeting this specific area will be critical to directly test the hypothesis that these blocks might derive from the collapse of an entrance.

Regardless of this possibility, data presented in this paper supports the hypothesis that Chamber 3 was within the endokarst at the time of animal visits. Carnivore bones, carnivore-modified fauna, macroscopic coprolites in Layer 4, and micromorphological evidence of phosphatic coprolites in Layer 2 (Figs. 5a-c; S10c-d) show that Chamber 3 may have served as a carnivore den, which more commonly occur within deeper cave spaces [1, 85–93]. However, while carnivore presence is demonstrated, establishing carnivores as the primary accumulating agent requires further systematic taphonomic quantification (e.g., assessing frequencies of tooth marks versus cut marks, and fragmentation patterns) of the assemblage. Alternatively, given the massive structural collapse, it is also plausible that carnivore remains were originally deposited in a higher vestibule and subsequently transported into Chamber 3.

Our data do not allow us to determine whether humans deposited lithic artifacts, charcoal, and burnt bones in Chamber 3 or in areas closer to our newly hypothesized cave entrance. Given the widely accepted preference of hominins for well-lit cave areas [12, 89, 94–96], we cannot exclude the possibility that archaeological materials initially accumulated near the hypothesized western entrance and were subsequently reworked into Chamber 3. The limited transport distance implied (≤ 10 m) would likely have had negligible impact on the preservation of lithic edge sharpness.

Layer 4, the deepest unit currently excavated, is a partial exception to the reworking evident in the overlying units, though the evidence for this is currently convergent rather than individually decisive, and should be read with that in mind. In the field, Layer 4 presents a looser sandy matrix, more consistently sub-horizontal coarse components, and better-preserved bone than Layers 2–3. Layer-by-layer spatial analysis is directionally consistent with this: Layer 4 shows only marginal, non-significant bone–lithic segregation ($p = 0.07$, Table S1), compared with significant segregation in both overlying Layers 2 and 3 ($p = 0.01$ each). This is not, on its own, a demonstration that Layer 4 is statistically distinct (the test result is a marginal non-rejection, not a significant positive finding) and it must also be weighed against the fact that Layer 4 remains only partially excavated, currently restricted to the southern sector of the chamber, and has not yet been sampled for micromorphological analyses. We treat the convergence of field texture, bone preservation, and a directionally consistent (if inconclusive) spatial signal as motivating, rather than confirming, the hypothesis that Layer 4 preserves a greater proportion of primary depositional context than the layers above it. Chamber 3 nonetheless remains under excavation, and it is probable that substantial sedimentary deposits persist below Layer 4.

Reaching these deeper, currently unexcavated units offers the most direct means of testing whether primary depositional context, and potentially in situ human occupation, survives within the chamber. We note that the sealing processes described here, while responsible for the site's invisibility, would also have isolated any such deposits from subsequent erosion, bioturbation, and anthropogenic disturbance.

5.1.2. Opening of subvertical entrance near Chamber 3, gravitational collapses, and palimpsest formation

The 8 m long normal fault we exposed in our open-air excavation is likely a segment of a 500 m long fault previously reported from the site [51] (Fig. 1a). This feature shows orientation similar to the 30 km-long Espiche-Odiáxere fault, one of the main regional Quaternary structures which is located just 5 km west from the site (Fig. 1a). We hypothesize that seismotectonic activity on the larger Espiche-Odiáxere fault caused the opening of the normal fault that crosses Gruta da Companheira (Figs. 1b-c; S12b). Slip movements along this local feature likely caused the progressive collapse of the site. The breccia layers that infilled the wedge open by the fault, exhibit chaotic to mosaic fabrics which are characteristic of fault and seismic-related breccias [76–80]. Furthermore, in the breccia and debris cone formed in front and inside Chamber 3, thin section analysis revealed frequent limestone fragments exhibiting sigmoidal veins with multilayered infillings of micrite, microsparite, and remobilized terra rossa (Figs. 5l; S10k-m). These features support the hypothesis that these deposits formed under recurrent extensional tectonic movement [84], compatible with the normal fault unearthed in our open-air excavation (Fig. 11b).

Our dataset suggests that the cave collapsed in three main phases:

(i) Partial roof collapse, debris cone formation, reworking of assemblages

The onset of tectonic activity probably caused early roof collapses in all chambers and triggered gravitational reworking of limestone boulders at the entrance of Chamber 3. Although mixing of human and carnivore assemblages might have commenced before tectonic rupture, the topographic gradients resulting from slip movement likely facilitated the mixing of archaeological and carnivore remains in this chamber. This remobilization phase is strongly supported by the dipping geometry of these cemented deposits in PNI (Fig. 2b), which slope towards the eastern wall of Chamber 3. Direct micro-

contextual evidence for physical reworking includes the vertical orientation of bones in Layer 2 (Fig S10e), alongside rotational galaxy features (Fig. 5k), subrounded terra rossa aggregates (Fig S10f), remobilized breccia fragments, and sedimentary relicts (Fig. 5e-f). This is further supported by the per-layer spatial statistical analyses: Layers 2 and 3 each independently show significant bone-lithic segregation (Table S1), indicating this is a property of the individual depositional packages and not only of the pooled assemblage. Together with the micromorphological and geometric evidence for collapse, this recurrence indicates that the bone and lithic assemblages of the upper units (Layers 3 – 2) underwent short-distance, gravity-driven redistribution. This redistribution appears to have rearranged materials only slightly rather than randomizing them: the recurrence of significant segregation across independently analyzed layers suggests that some of the original spatial structure, whether inherited from primary deposition or imposed by the redistribution process itself, has been preserved rather than erased.

(ii) Extensive roof collapse, main debris cone formation, reworking of assemblages

Possibly related with recurrent seismotectonic activity, a second and more intensive seismotectonic collapse caused the subsidence of cave ceilings in the hanging block north from the normal fault (as shown by the V-shaped morphology of Layer 103A; Figs. 2a; S12a-b), the blockage of the newly hypothesized western entrance, the opening of a narrow subvertical entrance closer to Chamber 3 [47], and consequently high rate rockfall/debris cone accumulation in front (Layers 103A to 104E) and at the entrance of this vestibule. The diffuse, interfingering contact observed between this debris cone and the underlying Layers 3 and 2 (Fig. 2b) suggests that the accumulation of debris at the entrance likely commenced simultaneously with the internal reworking of these units. This two-stepped process, an initial accumulation interfingering with Layers 3 and 2, followed by a second major phase, is further supported by the 3D plotting of boulder orientations (Fig. 6a). Both datasets suggest that a final major phase of gravitational accumulation filled most of the access to Chamber 3 and sloped into this chamber, pushing the previously accumulated boulders deeper into the cave and causing their upslope imbrication (Fig. 6a). Furthermore, given the catastrophic nature of this roof collapse, we cannot rule out the possibility that a portion of the archaeological assemblage derived from potential open-air occupations on the hilltop surface, though no physical traces of such occupations remain on the modern exterior.

Within the excavated area, lithics are concentrated toward the northeastern sector in Layers 2 and 3, and toward the southern sector in Layer 4 (Fig. 9), with faunal remains broadly overlapping these same zones. The combined-assemblage relative-risk surface additionally shows a smoothed gradient trending toward relative lithic over-representation in the north-west (Fig. 8a-d, f); as discussed in the Results, this reflects the estimator's known sensitivity to the sparsely excavated margins of the observation window, not an established feature of the assemblage, and we treat it as a prediction for future excavation rather than current evidence. The gravity-reworking hypothesis for Layers 2–3 therefore continues to rest on the geometric and micro-contextual evidence described above. The fresh state of the lithic edges confirms this was a short-distance remobilization process, while the subrounded edges of limestone fragments (Fig. 5a, d) point to intense post-fracture dissolution rather than mechanical abrasion.

(iii) Progressive stabilization

Outside Chamber 3, slip movements decreased, as shown by the transition from lower chaotic breccia with high rotational misfit (Layer 104C; Fig S11f) into upper mosaic breccia (Layer 104A, Figs. 5j; S11h) [76–80]. Furthermore, bioturbation (including fecal pellets and mite excrements) within these breccias (Fig S11c, e, g) indicates that the breakdown of the limestone bedrock occurred in episodic pulses interspersed with periods of seismotectonic stability.

5.1.3. Post-collapse diagenesis and final cave sealing

Following the collapse, the access to Chamber 3 became increasingly restricted (approx. 1–1.4 m wide), altering water and atmospheric circulation and thus favoring the brecciation of deposits along the northern profile (PNI - Layers 3 and

2; and PNO - Layers 104E-A) (Figs. 2b; 11), and comparatively less so within Layer 4, given its more distal location from the entrance and the main path of vadose water. This spatial pattern is corroborated by the SPPA, which identifies a highly structured, statistically significant northwest-to-southeast diagenetic gradient linking cementation type to distance from the collapsed entrance. This is consistent across Layers 2–4 individually as well as in the pooled assemblage. This points to long-term stability in the spatial constraints (entrance geometry and internal water routing), that structured post-collapse diagenesis, rather than a short-lived depositional event.

Within Chamber 3 and the lower exterior conduits, this restricted hydrology led to episodic waterlogged conditions. Importantly, we interpret this localized pooling as a direct result of the structural failure physically impeding internal drainage pathways. The micromorphological identification of isopachous crusts (Fig. 5e), localized stromatolitic textures (Fig. 5b), and distinct calcite cements provides straightforward evidence of these structurally induced, saturated environments [97–100]. A modest taphonomic divergence is also consistent with this picture: lithics are somewhat more often left uncemented than bones, a difference that could plausibly reflect the bone matrix's higher porosity and more reactive surface chemistry relative to denser lithic raw materials such as chert or greywacke. Though calcite coatings on lithics are also more prone to shedding during excavation which may inflate this contrast. More importantly, the pattern maps closely onto Layer 4's position outside the main zone of vadose pooling rather than onto any material-specific difference in cementation potential, reinforcing that the cementation gradient itself, not raw material, is the primary control on preservation state.

The final sealing of Chamber 3 is represented by Layer 1, a terra rossa unit deposited atop the debris cone (Fig. 11c). Among the units sampled micromorphologically, the complex, recrystallized carbonate aggregates in Layer 1 (Fig. 5i) are otherwise found only in the exterior near-surface soils (Layer 102; Fig. 5m–o), where they would have formed under near-surface weathering and soil-forming conditions. This correspondence indicates that Layer 1 accumulated by the washing-in of exterior surface sediment via gravity or sheet wash once the collapse had stabilized. The lithic artifacts and faunal remains within Layer 1 were therefore probably introduced by this same reworking, most plausibly eroded from the adjacent debris cone, and possibly derived from open-air occupation on the hilltop above, although no physical traces of such occupation survive. The uppermost exterior soil (Layer 101) records the final environmental shift of the site's exterior: a high concentration of silt-sized mica grains restricted to this layer (Fig S12f) indicates a distinct aeolian contribution under fully exposed, open-air conditions.

6. Conclusion

Our dataset enabled us to reconstruct three main phases of site formation:

1. **Original Pleistocene configuration:** Prior to collapses, the site likely functioned as a single, integrated gallery system with a sub horizontal entrance via the western hillside, some 10 m from Chamber 3. The location of this entrance is suggested by previous GPR data [47] and a distinct concentration of limestone boulders at the ground surface. Prior to collapse, Chamber 3 may have served as a carnivore den; however, given the evidence for structural reworking, it is also plausible that these faunal remains were transported into the chamber from higher-elevation vestibules alongside the archaeological assemblage. Our data do not allow us to confirm or deny whether humans also occupied this chamber or naturally lit vestibule(s) closer to the hypothesized entrance. Further excavations outside and inside Chamber 3 are needed to further explore these hypotheses.
2. **Multiphase seismotectonic disruption:** Collapse of galleries north-west from Chamber 3 was triggered by local extensional (normal) faulting, possibly related with larger compressional tectonic structures, as seen elsewhere in the region [36]. The collapse occurred as a multi-step phase and had a key role in the accumulation of lithic artifacts and faunal remains in Chambers 2 and 3.

3. **Cave sealing:** After collapse, the site transitioned into a progressive sealing environment dominated by structurally controlled water pooling, which led to the secondary carbonate cementation of lithic artifacts, animal bones, and sediments in Chamber 3. The same sealing that removed the site from surface visibility also isolated its deposits from subsequent erosion and disturbance; the deeper units of Chamber 3, still unexcavated, therefore remain the most promising target for recovering primary depositional contexts.

This multi-phased reconstruction is a working hypothesis, as no geochronological data are available from the site. Although absolute dating is ongoing, establishing a precise geochronological framework for the sequence so far unearthed is challenging due to the site's specific temporal and mineralogical parameters. Traditional chronometric techniques are severely constrained here: the techno-typological character of the assemblage suggests an antiquity beyond ~ 50 ka limit of radiocarbon dating, while the application of Optically Stimulated Luminescence (OSL) is hindered by the quartz-poor nature of the local karst and terra rossa sedimentary matrix. Consequently, to bypass these limitations, active dating efforts are currently concentrated on applying combined Uranium-Thorium (U-Th) and Electron Spin Resonance (ESR) methods directly to the recovered rhinoceros teeth remains.

Dating limitations aside, our results show that the formation of cave sites in southern Portugal may have been profoundly impacted by large scale geological processes. The intense tectonic and seismic activity identified here and elsewhere in the region acts as a profound geological masking agent, where exploitable karst structures were systematically weakened, collapsed, and sealed [36, 44, 101]. This process likely obscured the potential record of Paleolithic occupation from traditional surveys. Crucially, the identification of Gruta da Companheira suggests that these heavily sealed sites are present in the landscape and may be more numerous than the current record suggests. Consequently, we propose that prehistoric paleo-demographic levels in southern Portugal cannot be accurately assessed until the regional karstic record is thoroughly re-evaluated through the lens of structural geoarchaeology. The sealing conditions documented at Gruta da Companheira provide not only a reference for studying the opening and sealing dynamics of karst systems in the region, but also a foundational baseline for recognizing and decoding comparable geologically masked prehistoric sites.

Declarations

Author contributions

Guillermo Alzate-Casallas: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Software; Writing-original draft. **Lucía Cobo-Sánchez:** Formal analysis; Methodology; Writing-original draft. **João Cascalheira:** Conceptualization; Funding acquisition; Project administration; Supervision; Validation; Resources; Writing-original draft; Writing – review & editing. **Alvise Barbieri:** Conceptualization; Project administration; Supervision; Validation; Resources; Writing-original draft; Writing – review & editing.

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Data availability

The data supporting this study's findings are available in the Open Science Framework (OSF) repository at <https://osf.io/2x3vb/> (DOI: 10.17605/OSF.IO/2X3VB). This repository serves as the research compendium for our quantitative and qualitative analyses, providing access to all datasets and supplementary materials associated with this publication.

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