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Short communication

A revised, Last Interglacial chronology for the Middle Palaeolithic sequence of Gruta da Oliveira (Almonda karst system, Torres Novas, Portugal)

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ABSTRACT

Based on previous radiocarbon and U-series (Diffusion/Adsorption) dating of bone samples, the Middle Palaeolithic has been thought to persist at Gruta da Oliveira until ~37 thousand years (ka) ago. New U-series ages for stratigraphically constraining speleothems, coupled with new luminescence ages for sediment infill, show that the site's ~6 m-thick archaeological stratigraphy dates entirely within a <30 ka interval spanning substages 5a-5b of Marine Isotope Stage (MIS) 5. Significant technological change is observed across the sequence, akin to that seen in the Upper Palaeolithic over similar timescales. Flake-cleavers and bifaces, normatively definitional of the Vasconian facies, are restricted to a short interval correlated with Greenland Stadial (GS) 22, 85.1–87.6 ka ago. In cave and rock-shelter sites of southern and western Iberia, intact archaeological deposits securely dated to the ~37–42 ka interval remain elusive. Geological dynamics (e.g., erosion, sedimentation hiatuses, palimpsest formation) and human adaptive responses to climate-driven environmental change (e.g., abandonment of now forest-covered low- and mid-altitude karst areas, concentration of settlement in alluvial plains and coastal settings) are possible explanations for this pattern.

1. Introduction

The hypothesis that the Middle Palaeolithic persisted in Iberia long after the Upper Palaeolithic began elsewhere in Europe was proposed by Vega (1990) and Villaverde and Fumanal (1990) and developed into the "Ebro Frontier" model by Zilhão (1993, 2000, 2006a, 2009). Although based on culture-stratigraphic patterns and paleoenvironmental proxies, that model also used available chronometric results in a supporting role: defining the extent of the time lag involved.

Because of its implications for the population dynamics of late Neandertals and the modelling of their eventual assimilation (d'Errico et al., 1998; Zilhão, 2006b; Trinkaus, 2007), Ebro Frontier became a topic of much controversy, mostly focused on the reliability of the dating evidence. Owing to the exponential nature of radioactive decay and to the Middle-to-Upper Palaeolithic

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transition occurring close to the limit of applicability of radiocarbon, the younger-than-expected age estimates trusted by the model could simply result from incomplete decontamination (Wood et al., 2013).

Recent developments have not closed the debate. Using high-quality, ABOx (Acid-Base-Oxidation) charcoal dates, Zilhão et al. (2016, 2017) found strong support for Ebro Frontier in the Mula basin of Murcia (Spain). Here, it was not until ~37 ka (thousands of calendar years) ago that a modern human-associated archaeological culture, the Evolved Aurignacian, replaced the local, Neandertal-associated Middle Palaeolithic — five millennia later than in Catalonia and the Franco-Cantabrian region (Zilhão and d'Errico, 1999; Zilhão, 2006a; Wood et al., 2014, 2018; Morales et al., 2019) (Fig. 1A).

In contrast, using ultrafiltrated collagen, Wood et al. (2013) dated to >46,700 BP (OxA-23198, OxA-26440) a bone sample from the cave site of Zafarraya (Andalucía) previously dated to 33,300 ± 1200 BP (OxA-8999). Other purported late Middle Paleolithic cave sequences — namely, Gruta Nova da Columbeira (Portugal) and Jarama VI (Guadalajara, Spain) — were likewise shown to be much older than previously thought (Zilhão et al., 2011; Kehl et al., 2013; Wood et al., 2013).

Gruta da Oliveira (Torres Novas, Portugal; Fig. 1A) is one of the few other cave sites containing an occupation that has been dated to the interval of late Neandertal persistence posited by Ebro Frontier for southern and western Iberia: uppermost layer 8, which radiocarbon and Diffusion/Adsorption (D/A) U-series dating placed in the range of 35.6–38.6 thousand years (ka) ago (Marks et al., 2001; Hoffmann et al., 2013). TL (thermoluminescence) dating of heated flints, however, eventually showed that the 43–50 ka radiocarbon ages obtained for layer 14, half-way through the sequence, were vastly underestimated. At 77 ± 16 ka or 85 ± 16 ka (2σ errors) — depending on whether the external dose rate was calculated based on, respectively, the layer's more representative dosimeters or all of them — the TL results implied a significantly older age for layer 14, in MIS 4 or MIS 5 (Richter et al., 2014). Conceivably, therefore, the age of layer 8 could also be underestimated, the more so since its radiocarbon ages had been obtained on burnt bone, a material that is prone to produce unreliable results (Zazzo, 2014).

Here, we re-examine the chronology of Gruta da Oliveira. Using OSL (optically stimulated luminescence), we dated sediment samples collected from the extant profiles. Using U-series, we dated stratigraphically constraining speleothems. We find that the sedimentary succession is entirely of Last Interglacial age and that layer 8 does not support Ebro Frontier. The implications of these results are considered in the Discussion section.

2. Material and methods

The site belongs to the River Almonda karst, a multiphase maze cave system (Ford and Williams, 2007) developed in connection with an underground fluvial network. The outlets of this fluvial network have migrated to progressively lower elevations in response to tectonic- and erosion-induced changes along the Arrife overthrust fault, which has significantly uplifted the Central Limestone Massif of Estremadura above the Lower Tagus Tertiary Basin. In this locality, a vertically staggered arrangement of fossil passages was thereby generated. Eventually, the passage entrances became filled-up with archaeologically-rich deposits of Middle and Upper Pleistocene age. Gruta da Oliveira, located ~115 m asl (above modern sea level), ~40 m above the extant spring, is one such entrance (Fig. 1B-E).

At the time of discovery, the entrance was buried under slope deposits and a brecciated éboulis. The underlying Middle Palaeolithic succession of porch (Exterior), inward-adjacent (Access Corridor), and interior (27-S Chamber, Side Passage) areas, was archaeologically explored between 1989 and 2012 (Fig. 1F and G). Angelucci and Zilhão (2009), Deschamps and Zilhão (2018) and Zilhão et al. (2010a) provide detailed descriptions of site, excavation methods, stratigraphy and formation processes.

From bottom up, the archaeological sequence found below the colmatation material comprises six ensembles (Fig. 2A, S1-S2, S4-S5; the elevation of finds, plans and profiles was measured against an arbitrary datum set at 117.267 m asl):

- *Access Corridor Lower Ensemble (layers 23–25).* Archaeologically poor, silty sandy matrix filling the interstitial space between large boulders sub-vertically stuck between opposing walls, supporting the overlying stratification.
- *Access Corridor Middle Ensemble (layers 20–22).* Silty loam with few boulders, reflecting a period of stabilization during which the area was lived in, as shown by large, *in situ* hearth features (Fig. 1G).
- *Access Corridor Upper Ensemble (layers 15–19).* Silty loam with a variable clay component, filling the space between rockfall and containing lithic and faunal assemblages largely accumulated via low-energy displacement from habitation areas located in the unexcavated cave porch.
- *Basal Cave Interior (layers 13–14).* Silty loam accumulated behind a >20-ton, ~3 m-thick chunk of roof that fell onto the surface of layer 15 in grid units O–P/12–15; a fireplace at the base of layer 14 (Fig. S1) shows that this space — inner Access Corridor extending to the 27-S Chamber — was lived in.
- *Middle Cave Interior (layers 9–12).* Silty loam with anthropogenic faunal remains, stone tools and abundant coprolites, suggesting alternating use of the cave's much reduced interior space by hyaenas and humans.
- *Upper Cave Interior (layers 7–8).* Units burying the O–P/12–15 rock mass, eventually filling-up the cave; layer 7 is archaeologically sterile, while the layer 8 artefacts and faunal remains largely correspond to an inward, gravity-displaced tail of finds derived from the Exterior sector.

Layer 80, in the 27-S Chamber, is a remnant of the fluvial endokarst deposit formed when the cave was an active spring. It consists of cross-bedded, well-sorted sands with intercalated silt lenses, capped by a thick crust of cemented coarse sands.

Layers 26–27 (the Mousterian Cone) are found below and behind the Access Corridor, spilling onto the adjacent Passage of the Column. They form a loose, base-of-hourglass accumulation roofed by the layer 25 boulders.

Luminescence dating sample locations are shown in Figs. S1-S2. Luminescence ages were calculated using single-grain OSL (SG-OSL) and single-grain thermally-transferred OSL (TT-OSL) dating of quartz, and post-IR (Infra-red) infra-red stimulated luminescence (pIR-IRSL) dating of K-feldspar sub-samples.

In the Side Passage, layer 8 is capped by a multi-layered flowstone. Using U-series, Hoffmann et al. (2013) had dated layer 3 of a sample of that flowstone (sample X18-92; Figs. S1, S3). We dated its basal layer 4 using the isochron approach. We also used this approach to date two other speleothem samples that constrain the age of layers 26 (P15-569; Fig. S4) and 27 (R18-310; Fig. S5).

Unless otherwise specified, all U-series and luminescence ages are expressed with their 95.4% probability intervals (2σ uncertainties). The protocols and statistical methods used in the collection of samples and in the measurement, calculation and Bayesian modelling of their ages are detailed in the Supplementary Materials.

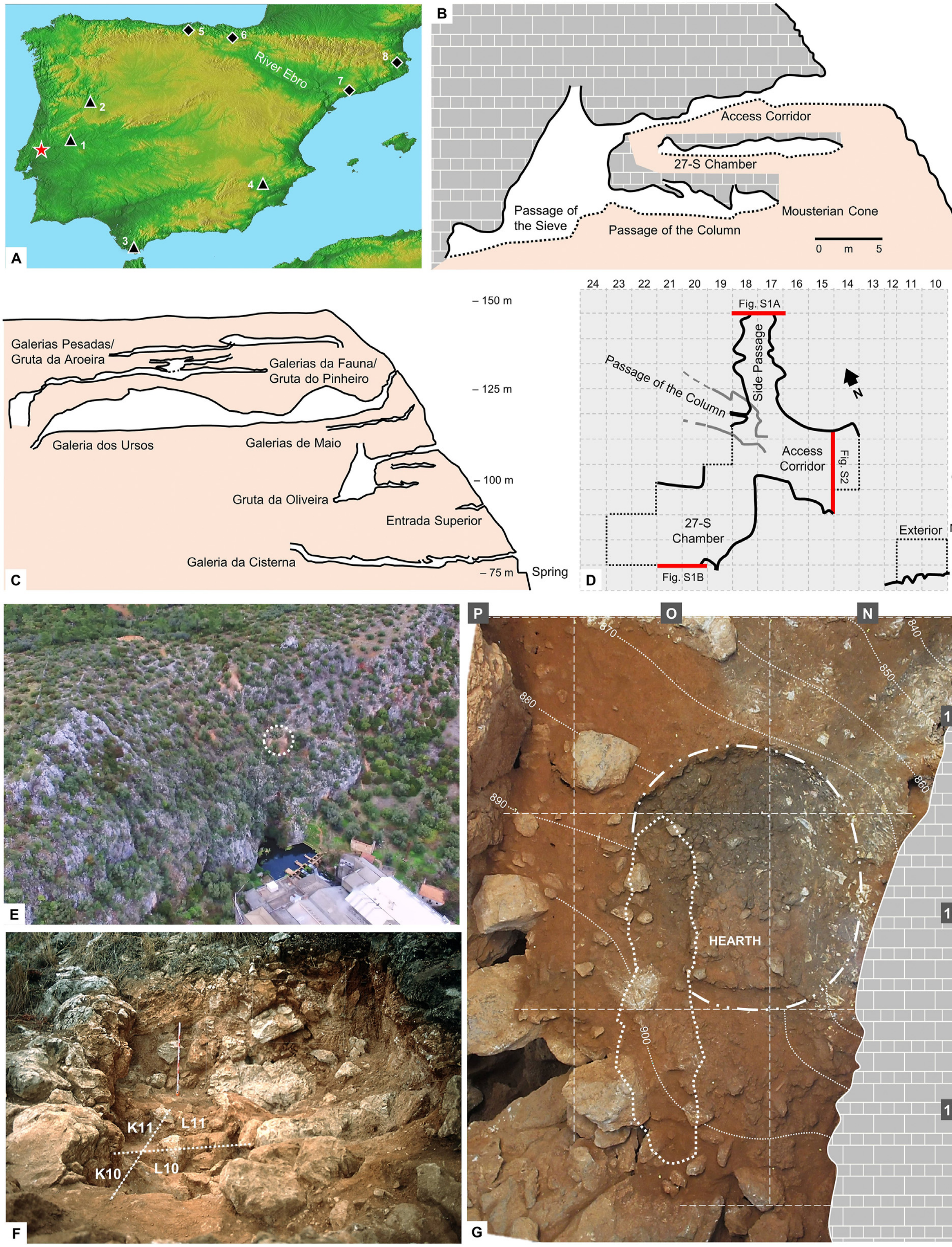

Fig. 1. Site and excavation. A. Location in Iberia. Star: Gruta da Oliveira. Triangles: Sites where the Middle Palaeolithic post-dates 40 ka (1. Foz do Enxarrique; 2. Cardina/Salto do Boi; 3. Gorham's Cave; 4. Cueva Antón). Diamonds: sites where the Upper Palaeolithic predates 40 ka (5. El Castillo; 6. Labeko Koba; 7. Cova Foradada; 8. L'Arbreda). **B.** Schematic section of the Galeria da Oliveira system of passages. **C.** Schematic section of the Almonda escarpment above the extant spring, showing the main passages and associated archaeological *loci*. **D.** Cave plan and excavation grid; wall contours are shown at the elevation of layer 10, and the red lines indicate the position of the sampled stratigraphic profiles illustrated in Figs. S1-S2. **E.** Drone overview of the Almonda escarpament; the position of the cave is indicated by the dotted circle. **F.** View of the Exterior area at the end of the 1991 field season, prior to complete removal of the collapse blocking the Access Corridor; layers 8–9 of the archaeological deposit below the collapse were partially excavated in grid units K-L/10–11 (stone tool refitting corroborates the correspondence of these units with the Access Corridor/Side Passage succession). **G.** End-of-décapage, orthorectfied zenithal view of layer 21 and its excavated hearth (filled with ash, Scots pine charcoal, burnt mammal bone and burnt tortoise carapace fragments); the outline of the fallen boulder that disturbed it along the northern edge is shown. Elevations are in cm below datum. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Results

U-series samples P15–569 and R18-310 yielded Holocene and Late Pleistocene ages (Table S2) that only apparently are at odds with their stratigraphic positions. As shown by stone tool refitting (Deschamps and Zilhão, 2018), layers 26–27 correspond to material percolated via voids found between the overlying sedimentary column and the encasing cave walls. The age obtained for R18-310 implies that, by 26.5 ka, the percolation paths had already become obstructed.

The age of the archaeological sequence (layers 8–25) is constrained by two dated speleothems: the flowstone sampled by X18-92 provides the *terminus ante quem*; the base of Crivo 1, a stalagmite growing out of the crust capping the sedimentary infill of the Passage of the Sieve, ~9 m lower down in Gruta da Oliveira's system of interconnected passages (Fig. 1C, S6; Table S1), provides the *terminus post quem*. We obtained an isochron age of 64/+29/-17 ka for basal layer 4 of X18-92 (Table 1; Fig. 2A), consistent with the age (93.2 ± 26.1) ka of overlying layer 3 (Table S1). The younger limit of the latter's probability interval is 67.1 ka and provides a minimum age for the uppermost unit of the underlying archaeological sequence, layer 8. A maximum age is provided by the older limit, 107.1 ka, of the probability interval obtained for the base of Crivo 1 (104.4 ± 2.7 ka; Fig. 2A). In short, we can now confidently conclude that layers 8–25 span at most thirty millennia (the 67.1–107.1 ka interval; Fig. 2A).

Richter et al.'s (2014) combined dosimetry TL ages are consistent with these U-series constraints, and so are our OSL results (Table 2; Fig. 2). The TL age for layer 13 (68 ± 18 ka) sets a maximum age of 86 ka for the overlying, OSL-dated layers 8, 9 and 11. Given the *terminus ante quem* of 67.1 ka provided by flowstone sample X18-92, the age of layers 8–11 must therefore lie within the 67.1–86.0 ka interval. Likewise, the age of layer 22 is bounded by the *terminus post quem* (107.1 ka) provided by the base of the Crivo 1 stalagmite and by the younger limit (80.9 ka) of the probability interval of its own OSL age (109.3 ± 28.4 ka).

4. Discussion

4.1. Site formation

Two previously dated speleothems yielded the following basal ages (Table S1; Figs. S7-S8): 191.3 ± 19.2 ka, for a stalagmite growing on a bedrock ledge in the corner between the Access Corridor and the 27-S Chamber, at an elevation of ~111.3 m asl (O17-1177); and 163.7 ± 6.8 ka for a loose stalagmite with a clean base retrieved in the éboulis formed by the major roof and wall collapse found at the interface between layers 19 and 20 (P17-1047). Therefore, by 172 ka at the latest, the water table had descended to below 111 m asl. The luminescence ages for the layer 80 sample (Table 2), ~109.9 m asl, are consistent with this conclusion, as they imply that, after 220–235 ka, a fluvial hydrological regime had ceased to exist higher-up in the system.

The >100,000-year lag between the end of endokarst fluvial sedimentation and the initial build-up of the archaeological sequence suggests that, throughout, the base of the Access Corridor (where bedrock is found at ~108 m asl) and adjacent passages remained in the epiphreatic zone, the site functioning as an overflow spring. This would have precluded the accumulation of a sedimentary infill, even though the former fluvial outlet now provided a path for the penetration of colluvial material and, higher-up, the cave system had become part of the vadose zone. The water-worn external surfaces of Crivo 1 and close-by stalagmites (Fig. S6) are consistent with this interpretation, as they imply intermittent waterflow at the elevation of this passage, ~103 m asl, until after 101 ka.

Our reconstruction of the position of the epiphreatic zone implies that, during MIS 5, the cave may have been perched no more than 5–10 m above the then-extant spring. This setting is similar to Galeria da Cisterna's, located lower down in the Almonda escarpment (Fig. 1C) and containing breccia remnants that yielded Solutrean and Magdalenian stone tools and faunal and human bone remains (Zilhão, 1997; Trinkaus et al., 2011).

4.2. Sources of dating error

Incomplete removal of contaminants is the likeliest explanation for the underestimated radiocarbon ages. The explanation for why the U-series (D/A) dates also turned out to be minimum ages is hinted at by the results in the range of 19.6–31.5 ka obtained for speleothems found in variable stratigraphic relationship with the archaeological sequence: the flowstone capping reworked layer 27 (R18-310; Table S2; Fig. S5); the thick calcite infillings of voids between the sedimentary column and the wall found at the elevation of layers 13–14 of the Access Corridor (R16–288 and R16-295; Table S1); and the flowstone capping the deposit in the 27-S Chamber (L22-1; Table S1; Fig. S1).

These U-series ages show that, during the LGM (Last Glacial Maximum), long after sediment accumulation had ended and despite the original entrance to the cave having become sealed by collapse since the Middle Palaeolithic (Fig. 1F), much water was percolating through the site's different passages. A possible cause for this increase is a wetter climate (Ellwood et al., 1998). Alternatively, a coldness-related denudation of the exokarst may have made for unobstructed infiltration of rainwater through the numerous, nowadays sediment-cluttered vertical fissures connecting the cave with the ground surface above.

Such processes would have resulted in complex bone uranium uptake histories, most likely involving episodes of enrichment that the D/A approach was unable to detect, explaining why it underestimated the ages. The D/A model assumes the predominant uranium uptake process is diffusion with simultaneous adsorption onto the large internal surface area of the bone mineral. It predicts ∪-shaped 'profiles' across the bone section of both U concentration and ^{230}Th/U ratios that gradually flatten to uniform profiles as the bone reaches equilibrium with uranium in the burial environment. For relatively constant geochemical conditions, the parameters of the model can be estimated from the shape of the U concentration, and the ^{230}Th/U corrected for the uptake of uranium to obtain a D/A date. For bones that are far from equilibrium with the uranium in the burial environment, more complex geochemical histories (e.g., the leaching or recent uptake of uranium) can be identified from the shapes of the profiles, and the bones rejected as unsuitable for D/A modelling. However, if the bone re-equilibrates with the new geochemical conditions, the profiles will be uniform and the complex geochemical history will go undetected, resulting in inaccurate D/A dates.

The uniform U and ^{230}Th?U 'profiles' of the previously dated bones showed them to be close to or at equilibrium. Therefore, because of the possibility of fast re-equilibration with changing geochemical conditions, the accuracy of the U–Th ages could not be guaranteed, as indeed Hoffmann et al. (2013) acknowledged.

4.3. Chronostratigraphy

Plotted against global records (Rasmussen et al., 2014), our U-series and luminescence ages place the bulk of the archaeological sequence in MIS 5a, ~71–85 ka ago (layers 8–14) and MIS 5b, ~85–93 ka ago (layers 15–22) (Fig. 2B). Additional precision can be obtained if we consider the stratigraphic position of the episodes of

Table 1
U-series age of basal layer 4 of Gruta da Oliveira sample X18-92 (flowstone capping the Side Passage succession; 2σ uncertainties).

Sub-sample	Lab #	^{238}U (ng/g)	^{232}Th (ng/g)	($^{230}Th/^{232}Th$) activity ratio	($^{232}Th/^{238}U$) activity ratio	($^{230}Th/^{238}U$) activity ratio	($^{234}U/^{238}U$) activity ratio	Age (ka) uncorrected	Age (ka) corrected	($^{234}U/^{238}U$)$_{initial}$ activity ratio corrected
Isochron I #1	UEVA 518	67.56 ± 0.26	87.86 ± 0.32	1.47830 ± 0.00773	0.4269 ± 0.0009	0.62903 ± 0.00364	1.13430 ± 0.00272	86.499 ± 0.823	48.504 ± 20.422	1.2339 ± 0.0616
Isochron I #2	UEVA 519	70.78 ± 0.32	96.11 ± 0.44	1.40272 ± 0.00769	0.4457 ± 0.0009	0.62320 ± 0.00371	1.14775 ± 0.00291	83.685 ± 0.810	44.258 ± 21.357	1.2602 ± 0.0729
Isochron I #3	UEVA 520	70.51 ± 0.34	111.58 ± 0.54	1.20368 ± 0.0835	0.5194 ± 0.0011	0.62320 ± 0.00449	1.14054 ± 0.00328	84.550 ± 0.985	36.434 ± 27.828	1.2665 ± 0.0962
Isochron I #4	UEVA 521	68.58 ± 0.54	83.68 ± 0.67	1.53946 ± 0.01349	0.4006 ± 0.0009	0.61470 ± 0.00518	1.19076 ± 0.00374	77.406 ± 1.002	44.325 ± 16.948	1.3182 ± 0.0749
Isochron I #5	UEVA 1796	68.96 ± 0.37	94.38 ± 0.56	1.36902 ± 0.00825	0.4492 ± 0.0009	0.61303 ± 0.00384	1.09110 ± 0.00305	88.755 ± 0.943	46.028 ± 24.437	1.1620 ± 0.0478
Isochron I #6	UEVA 1797	69.55 ± 0.34	94.75 ± 0.44	1.39009 ± 0.00725	0.4472 ± 0.0009	0.61959 ± 0.00348	1.09216 ± 0.00276	90.062 ± 0.865	47.658 ± 24.111	1.1642 ± 0.0480
Isochron I #7	UEVA 1798	65.74 ± 0.33	81.20 ± 0.40	1.53484 ± 0.00978	0.4054 ± 0.0009	0.62031 ± 0.00394	1.09387 ± 0.00280	89.984 ± 0.959	52.425 ± 20.689	1.1611 ± 0.0406
Isochron I #8	UEVA 1799	66.40 ± 0.29	89.83 ± 0.40	1.40839 ± 0.00775	0.4441 ± 0.0009	0.62342 ± 0.00410	1.09146 ± 0.00275	91.017 ± 1.001	48.947 ± 23.842	1.1629 ± 0.0471
Isochron I #9	UEVA 1800	73.92 ± 0.39	101.48 ± 0.56	1.42424 ± 0.00836	0.4506 ± 0.0009	0.63976 ± 0.00395	1.09380 ± 0.00310	94.397 ± 1.023	51.745 ± 24.028	1.1698 ± 0.0500
Isochron *Age*I									83^{+92}_{-29}	
Isochron II #1	UEVA 1801	55.17 ± 0.48	86.97 ± 0.69	1.25202 ± 0.01232	0.5175 ± 0.0010	0.64584 ± 0.00681	1.08910 ± 0.00371	96.540 ± 1.714	45.476 ± 30.388	1.1729 ± 0.0639
Isochron II #2	UEVA 1803	63.22 ± 0.33	90.03 ± 0.48	1.37329 ± 0.00881	0.4675 ± 0.0009	0.63993 ± 0.00438	1.09189 ± 0.00302	94.724 ± 1.115	49.975 ± 25.581	1.1690 ± 0.0528
Isochron II #3	UEVA 1804	57.23 ± 0.32	81.41 ± 0.46	1.35545 ± 0.00946	0.4669 ± 0.0009	0.63089 ± 0.00471	1.08826 ± 0.00324	93.180 ± 1.184	48.248 ± 25.891	1.1615 ± 0.0507
Isochron II #4	UEVA 1805	56.49 ± 0.31	83.22 ± 0.44	1.37406 ± 0.00819	0.4835 ± 0.0010	0.66227 ± 0.00428	1.09460 ± 0.00326	99.588 ± 1.162	53.163 ± 26.454	1.1793 ± 0.0587
Isochron II #5	UEVA 1806	61.18 ± 0.55	97.54 ± 0.87	1.25437 ± 0.01060	0.5233 ± 0.0010	0.65436 ± 0.00597	1.09214 ± 0.00364	98.083 ± 1.542	46.527 ± 30.579	1.1808 ± 0.0677
Isochron II #6	UEVA 1807	54.94 ± 0.27	75.01 ± 0.36	1.39706 ± 0.00871	0.4482 ± 0.0009	0.62412 ± 0.00423	1.09001 ± 0.00289	91.383 ± 1.042	48.755 ± 24.257	1.1610 ± 0.0473
Isochron II #7	UEVA 1808	55.67 ± 0.26	74.63 ± 0.35	1.46652 ± 0.00850	0.4400 ± 0.0009	0.64326 ± 0.00435	1.08896 ± 0.00281	95.952 ± 1.113	54.280 ± 23.366	1.1601 ± 0.0456
Isochron Age II									70^{+38}_{-28}	
All data combined									64^{+27}_{-17}.	

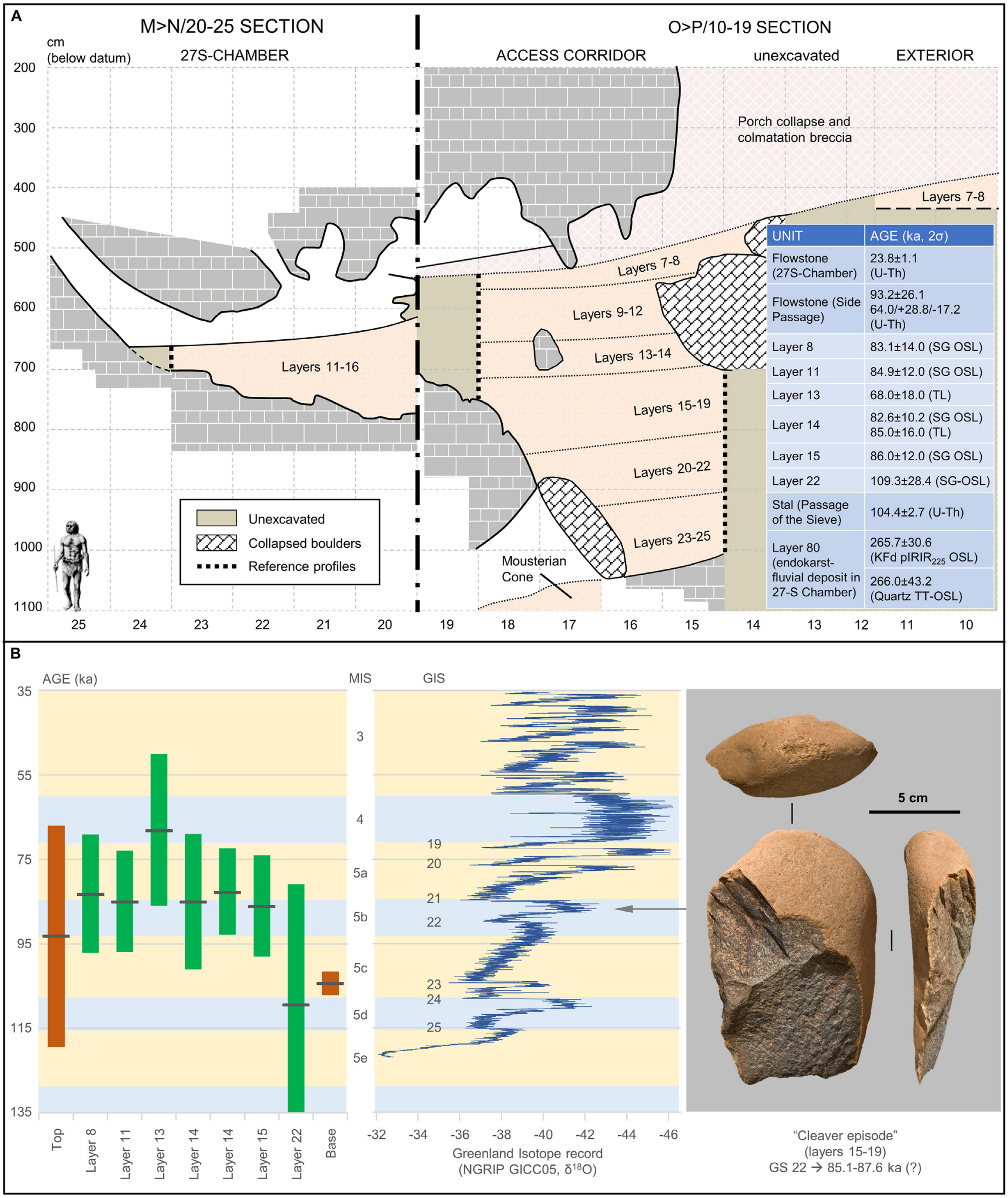

Fig. 2. Stratigraphy and dating. A. Schematic stratigraphic profile and summary of luminescence and U–Th results for the archaeological sequence and the speleothems that constrain its age (2σ uncertainties). The TL age calculations are based on the average external dose rates obtained when all the dosimeter results are taken in account (Richter et al., 2014). Elevations are in cm below datum. The offset between the two sections is an artefact of their being 2 m apart along the x-axis of the excavation grid. **B.** Plot of the ages against global records (2σ uncertainties). The dark orange bars represent the constraints provided by U-series; the green bars represent the luminescence ages for different stratigraphic units of the succession. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Final luminescence ages for the Gruta da Oliveira succession.

Sample	Layer	Dating method	Mineral	Grain size (μm)	Total dose rate (Gy/ka) [a]	Age Model [b]	D_e (Gy)[a]	Age (ka) [a]
AMD16-1	8	Single-grain OSL	Quartz	212–250	1.69 ± 0.09	MAM-3	140.9 ± 9.0	**83.1 ± 7.0**
AMD16-2	11	Single-grain OSL	Quartz	212–250	1.84 ± 0.09	MAM-4	156.3 ± 6.9	**84.9 ± 6.0**
AMD16-7	14	Single-grain OSL	Quartz	212–250	2.03 ± 0.10	MAM-4	167.3 ± 5.0	**82.6 ± 5.1**
AMD16-6	15	Single-grain OSL	Quartz	212–250	2.01 ± 0.10	MAM-4	173.3 ± 7.8	**86.0 ± 6.0**
AMD16-8	22	Single-grain OSL	Quartz	212–250	1.44 ± 0.08	MAM-3	157.7 ± 18.5	**109.3 ± 14.2**
AMD16-5	80	Single-grain TT-OSL	Quartz	212–250	1.46 ± 0.07	CAM	388.0 ± 23.5	**266.0 ± 21.6**
AMD16-5	80	$pIRIR_{225}$	KFd	90–125	2.02 ± 0.09	CAM	537.4 ± 17.7	**265.7 ± 15.3**

[a] Mean ± total uncertainty (1σ or 68% confidence interval), calculated as the quadratic sum of the random and systematic uncertainties.
[b] CAM = central age model; MAM-3 = three-parameter minimum age model; MAM-4 = four-parameter minimum age model (Galbraith et al., 1999).

increased temperature and humidity revealed by interstratified flowstone (Angelucci and Zilhão, 2009).

Given its OSL age, layer 8 cannot be younger than 69.1 ka, and it is separated from layer 3 of the overlying flowstone, dated to >67.1 ka, by a significant thickness of calcite; the latter's precipitation must therefore have begun no later than GI (Greenland Interstadial) 19, 69.4–72.3 ka ago. Further down in the sequence, significant flowstone formation occurs between (a) layers 14 and 15 (suggesting correlation with GI 21, which began 84.8 ka ago, and in agreement with the age of layers 13 and 15, <86.0 and 86 ± 12 ka, respectively), and (b) layers 19 and 20 (suggesting correlation with GI 22, which began 90.0 ka ago).

Bayesian modelling suggests that the archaeological sequence starts in the later part of MIS 5c (Fig. S12). Down to the lowermost unit for which we have data (layer 22), the charcoal assemblages are overwhelmingly dominated by *Pinus sylvestris*, whose present range in Portugal lies >1000 m above the elevation of the Almonda spring (Badal et al., 2012) — implying that most sediment deposition occurred during stadial intervals. It is therefore unlikely that layers 20–22 accumulated during the earlier, warm parts of the long GI 23 interstadial (90.1–104.5 ka ago).

Based on the reasoning above:

- layers 8–14 likely date to GS 20 (72.3–74.1 ka ago) and GS 21 (76.4–77.8 ka ago), with the carbonate incrustation seen across the site at the interface between layers 12 and 13 possibly reflecting the intervening, short GI 20 interstadial;
- layers 15–19 likely date to GS 22 (85.1–87.6 ka ago);
- layers 20–22 likely date to GS 23, a very short quasi-stadial, and the cooler end of GI 23 (90.1 to approximately 92.0 ka ago).
- layers 23–25 likely date to the earlier, warmer parts of GI 23 (>92 ka ago).

A corollary of this chronostratigraphic model is that, in western Iberia, significant and rapid technological change was taking place towards the end of the Last Interglacial. Layer 22 features a flint-dominated Levallois industry (mostly preferential and, secondarily, recurrent unipolar) in which quartzite is reduced in similar manner, while layers 18–19 are quartzite-dominated and reduction is via preferential Levallois debitage for flint and a centripetal method producing very few Levallois flakes for quartzite (with substantial amounts of Kombewa products being additionally extracted from blanks of both raw-materials) (Deschamps and Zilhão, 2018). In addition, layers 18–19 contain a number of flake-cleavers and bifaces, which are also found in layers 15–17 but never above (in layers 8–14) or below (in layers 20–25).

Given available constraints for layers 15–19, this "cleaver episode" probably lasted no more than some two-and-a-half millennia, and the duration returned by Bayesian modelling for the other units of the succession is of the same order of magnitude (Table S9; Fig. 2B). Thus, across the timespan of ~15,000 years represented by the Access Corridor Middle Ensemble (layers 20–22), the Access Corridor Upper Ensemble (layers 15–19), and the Basal Cave Interior (layers 13–14), the rhythms of technological change are not qualitatively different from those of the Upper Palaeolithic (cf. the 20,000 years spanned by the sequence of Aurignacian, Gravettian and Solutrean, and the latter's duration of about three millennia).

4.4. Palaeoanthropological significance

Gruta da Oliveira joins the list of cave sites where the late persistence of the Middle Palaeolithic suggested by radiocarbon dating is illusory. However, support for that persistence pattern remains strong based on the evidence derived from riverine contexts dated by both radiocarbon and luminescence. Besides Cueva Antón, where the fluvial succession is preserved under the overhang of a rock-shelter (Angelucci et al., 2013; Zilhão et al., 2010b, 2016, 2017), such is the case with two open-air Portuguese localities in the Tagus and Côa river valleys (Foz do Enxarrique and Cardina/Salto do Boi, respectively) (Cunha et al., 2019; Aubry et al., 2020).

The hitherto available evidence suggested that Gruta da Oliveira was a karst archive spanning all of the Iberian Middle Palaeolithic, from MIS 5 to late MIS 3, but it is now clear that the archaeological sequence represents <30,000 years within MIS 5a, MIS 5b and late MIS 5c. This limitation in time translates into increased resolution in stratigraphy. The site can now be seen as a detailed record of human adaptation during a little-known but critical period of the archaeology of Europe and its Neandertal inhabitants — one witnessing the emergence of fisher-hunter-gatherer economies, personal ornaments, and cave painting (Hoffmann et al., 2018a, 2018b; Zilhão et al., 2010b, 2020).

Of particular significance is that, in the region, the production of flake-cleavers and bifaces would seem to be restricted to the two-and-a-half millennia of the GS 22 stadial (Fig. 2B). Such macro-tools have been used to define the so-called Vasconian facies of the Franco-Cantabrian Middle Palaeolithic, whose chronology remains controversial (Deschamps, 2017). A number of French occurrences would seem to date to MIS 3, while some Cantabrian sites (e.g., La Verde, El Hondal) have been assigned to the Last Interglacial on stratigraphic grounds. Gruta da Oliveira shows that the phenomenon extends to the western façade of Iberia, where it may well be restricted to a rather narrow time window within MIS 5b.

5. Conclusion

At present with three possible exceptions only — Context 16 of Stringer and Barton's 1990s excavation of Gorham's Cave (Gibraltar) (Pettitt and Bailey, 2000; Zilhão and Pettitt, 2006), layers L-P of Gruta do Caldeirão (Tomar, Portugal) (Ellwood et al., 1998; Zilhão, 1997, 2000, 2006a), and levels GG-II of Lapa do Picareiro (Haws et al., 2020) — the archaeology of the 37–42 ka interval would seem to be missing from karst archives of southern and western Iberia. Climate-driven geological processes, human response to environmental change, and research biases underpin this pattern. The extreme changes in vegetation cover experienced by the peninsula as global climate transitioned from the very cold/dry spell of HE (Heinrich Event) 4 to the rather long and temperate GI 8 interstadial (Fletcher and Sánchez Goñi, 2008; Sepulchre et al., 2007) must have entailed hiatuses of either erosion or deposition. In addition, the highland and karst areas that GI 8 densely forested are the kinds of places that have been the preferential, if not exclusive focus of Spanish Middle Palaeolithic Archaeology — but the dense tree cover those places then gained may have resulted in their being largely abandoned by humans (as would seem to have been the case during the Early Holocene). As previously argued (Zilhão et al., 2016), to overcome the current lacunae in our knowledge of the later Middle Palaeolithic of southern and western Iberia we need to develop research programs targeting open-air settings along rivers, lake margins and the seaside.

Credit statement

João Zilhão: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition, Diego E. Angelucci: Conceptualization, Investigation, Writing – review & editing, Lee J. Arnold: Conceptualization, Investigation, Writing – review & editing, Funding acquisition, Martina Demuro: Conceptualization, Investigation, Writing – review & editing, Funding acquisition Dirk L. Hoffmann: Conceptualization, Investigation, Writing – review & editing, Funding acquisition Alistair, W. G. Pike: Conceptualization, Investigation, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2021.106885.

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