



HAL
open science

35,000 years of recurrent visits inside Nerja cave (Andalusia, Spain) based on charcoals and soot micro-layers analyses

M^a Ángeles Medina-Alcaide, Ségolène Vandeveldel, Anita Quiles, Edwige Pons-Branchu, Iñaki Intxaurbe, José Luis Sanchidrián, Hélène Valladas, Damien Deldicque, Catherine Ferrier, Eva Rodríguez, et al.

► To cite this version:

M^a Ángeles Medina-Alcaide, Ségolène Vandeveldel, Anita Quiles, Edwige Pons-Branchu, Iñaki Intxaurbe, et al. 35,000 years of recurrent visits inside Nerja cave (Andalusia, Spain) based on charcoals and soot micro-layers analyses. *Scientific Reports*, 2023, 13 (1), pp.5901. 10.1038/s41598-023-32544-1 . hal-04086896

HAL Id: hal-04086896

<https://hal.science/hal-04086896v1>

Submitted on 2 May 2023


HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



OPEN

35,000 years of recurrent visits inside Nerja cave (Andalusia, Spain) based on charcoals and soot micro-layers analyses

M^a Ángeles Medina-Alcaide^{1,2}, Ségolène Vandeveldé³, Anita Quiles⁴, Edwige Pons-Branchu³, Iñaki Intxaurbe⁵, José Luis Sanchidrián², Héléne Valladas³, Damien Deldicque⁶, Catherine Ferrier¹, Eva Rodríguez² & Diego Garate⁷

Charcoal and micro-layers of soot trapped in speleothems from the inner galleries of Nerja Cave were analysed through an interdisciplinary study. The absolute dating of the prehistoric subterranean activity of the cave and the identification of different phases of visits to the deep parts are presented and discussed. The charcoal analysis includes anthracological analysis and SEM–EDX. The soot analysis includes optical microscopy, Raman spectroscopy and TEM–EDX, and the microcounting of soot microlayers. The ¹⁴C dating of 53 charcoals identified 12 phases of prehistoric visits to the cave between 41,218 and 3299 cal. BP, putting back the origin of human occupation of this emblematic cave by 10,000 years. The interdisciplinary analysis of the soot microlayers allowed us to perform a high-precision zoom on the last three visitation phases identified by Bayesian analysis (8003–2998 cal. BP.), demonstrating that these phases contain at least 64 distinct incursions, with an average of one visit every 35 years for the Neolithic period. Spatial analysis showed that not all areas of the cave were used in the same periods, highlighting the repetition of visits to certain specific sectors of the Lower Galleries of the cave. Lastly, the anthracological data indicate a cross-cultural and unique use of *Pinus tp. sylvestris-nigra* wood for lighting activities over an extended period between the Gravettian and Upper Magdalenian.

Deep karst visits during the Paleolithic are known by remains such as rock art, fire remains or even human constructions such as the one found at Bruniquel cave¹. It is however difficult to determine if these remains were left by single visits or recurrent ones, as they are often found on the soil surface in caves, devoid of a time-stratigraphic context to provide chronological support. Here, by the ¹⁴C dating of more than 60 samples of lighting and fire remains (charcoals and soot layers) and two abstract rock art representations, we are able to present a robust Bayesian model that constrains the periods of occupation for the internal prehistoric activity in Nerja cave. Using the multi-analytical identification and micro-counting of soot layers trapped in a stalagmite, we also provide the minimum number of visits and their recurrence.

Nerja Cave (Malaga, Andalusia, Spain) is one of the main sites for the study of prehistoric groups in the Western Mediterranean. An extensive archaeological and palaeontological sequence has been recovered in its entrance rooms, including remains from the Gravettian, Solutrean, Magdalenian, Epipalaeolithic, Neolithic and Chalcolithic chrono-cultures. From the discovery of the cave (1959) to the present day, this sedimentary deposit has been examined by different research teams, resulting in extensive scientific and cutting-edge knowledge (including numerous radiocarbon dates) about the prehistoric inhabitants of Southwest Europe^{2–6}.

¹Université de Bordeaux, UMR CNRS 5199 PACEA, Bâtiment B2 Allée Geoffroy Saint Hilaire, 33600 Pessac, France. ²Universidad de Córdoba, HUM-781, 14071 Córdoba, Spain. ³Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, 91191 Gif-sur-Yvette, France. ⁴Institut Français d'Archéologie Orientale, Pôle Archéométrie, Cairo, Egypt. ⁵Departamento de Geología, Euskal Herriko Unibertsitatea/Universidad del País Vasco, 48940 Leioa, Spain. ⁶Laboratoire de Géologie, Département de Géosciences, École Normale Supérieure, CNRS, UMR 8538, PSL University, Paris, France. ⁷Instituto Internacional de Investigaciones Prehistóricas de Cantabria (IIIPC), Universidad de Cantabria, 39005 Santander, Spain. ✉email: maria-de-los-angeles.medina-alcaide@u-bordeaux.fr

The interior spaces of the cave are structured by a large endokarst volume of more than 4.8 km of topographic development, in which there are numerous slopes and complex speleological passages. Sunlight does not penetrate these areas and artificial lighting is essential for access. These sectors have received less archaeological attention since the discovery of the cave, although they contain a unique wealth of heritage, including one of the most richest and oldest Palaeolithic Art sites in southern Spain⁷.

In recent years, the study of the Internal Archaeological Context (henceforth IAC)^{8,9} has been prioritized, through an intensive revision of the walls and floors of the internal galleries, as well as through the use of new technologies on site (DStretch software, digital portable microscope, etc.) for the detection and preliminary analysis of different remains of prehistoric subterranean occupation, followed by their laboratory analysis. This has enabled a holistic and up-to-date understanding of the different uses and visits to the deep areas of the cave. Likewise, the number of cave motifs found has considerably increased and numerous traces of the different Pleistocene and Holocene visits to the interior of the cave have been discovered. These are linked to subterranean activities of a heterogeneous nature, including the execution of Palaeolithic graphic manifestations⁷, the Palaeolithic modification of the endokarst geomorphology¹⁰ and the use of the cave for burial purposes during the Recent Prehistoric period¹¹.

Most of the archaeological remains found on the floor of the internal areas of Nerja cave are pieces of charcoal from the woody fuel used for lighting the cave during prehistoric times. These residues correspond to the lighting of fires and fixed “lamps” but, above all, to the use of wooden torches^{12–15}. As our previous experimental research indicates¹⁶, the charcoal from the torches is usually found scattered and isolated, with no other combustion residue nearby, the result of its intermittent detachment during human transit carrying this lighting tool (like the breadcrumbs in the story of *Hansel and Gretel*). In this regard, these lighting residues (charcoals from prehistoric lighting systems) are remains from the different prehistoric visits. Their ¹⁴C dating allows the chronological determination of prehistoric underground activity, as well as knowledge of the unique or multiphasic nature of the prehistoric activity inside the cave.

In this paper we present the first high-precision Bayesian model for the chronological, multi-phase, absolute-scale characterisation of different prehistoric visits to the deep sectors of Nerja cave. The paper includes 68 radiocarbon datings (48 of them unpublished) carried out by two different laboratories, in USA (Beta Analytic) and in France (Laboratoire des Sciences du Climat et de l’Environnement, first on the Tandétron then on Artémis, LMC14). Before their inclusion in the Bayesian model, the dates were subjected to a “validation filter”³ based on analytical and physico-chemical criteria, in order to robustify the model. In addition, the results have been linked to other chronometers, in particular, to 7 new ¹⁴C datings on carbonates from a stalagmite with soot microlayers to provide the model with greater accuracy and resolution. In total, 35,000 years of human occupation in the deep karst and at least 64 different phases have been identified, so far the largest number of visits known for a prehistoric cave in Europe.

Materials and methods

The materials examined are combustion residues, mainly charcoal pieces and soot microlayers, from different lighting systems used during prehistoric times to enter the deep areas of the cave, as well as some of the tiny charcoal particles from the pigment of black marks located on the cave walls. Charcoal was identified through anthracological analysis including SEM–EDX. Soot microlayers, located inside a small stalagmite collected, were studied through optical microscopy observation and characterized with Raman spectroscopy and TEM–EDX analysis. The ¹⁴C dates obtained on these residues of charcoal and soot were then subjected to a Bayesian analysis using Oxcal 4.4 (after performing a “validation test” on each sample) to identify the different phases of the visits inside the cave, the transition intervals and the duration of each visit. Finally, the visits of the Holocene phases obtained through Bayesian analysis were refined by micro-counting the numerous layers of soot inside the stalagmite. More detailed information on the methodology followed can be found in the Supplementary Information (S1).

Three types of sampling plan were employed depending on the nature and localization of the samples:

- (a) *Samples from the floor* An aseptic collection technique was developed for charcoal lying on the floor, in interstices or cavities at surface or semi-surface level. All rooms with prehistoric human occupation were sampled. The number of samples per room was proportional to the number of charcoals located in each sector, with the aim of obtaining a representative chronological approximation on a global scale. Sampling began in an elevated room, the Cascade Room, in order to avoid dating samples linked to external sedimentary deposits that may have migrated or percolated inside the cave through different taphonomic processes. The tourist remodelling of some areas of the cave was the main limitation for the sampling of some internal sectors. We therefore sampled only residues that had not undergone intense post-depositional movements. Thus, 66 charcoal pieces samples were selected from the floor. Of these samples, four came from the interior of concavities interpreted as possible “lamps” or “fixed combustion points”^{12–14} (Fig. 1B) (numbers 28, 43, 65, 66, see Supplementary information S2), and 3 from the interior of possible fixed fires (numbers 60, 64, 36, Supplementary information S2). Samples 11 and 14 relate to the possible wick of a lamp on a shell¹⁵. The other samples are scattered charcoal, without the presence of other combustion residues nearby; based on the dispersion of remains from previous experimental activities¹⁶, we relate these remains to the use of wood torches. Although the remains were generally found at surface level (Fig. 1C), we occasionally made small probes to locate residues a few centimetres deeper, especially for the detection of combustion residues located inside the fixed “lamps”.
- (b) *Samples from black marks* tiny particles (< 2 mm) of charcoal pigment from 2 black marks present on the cave walls were micro-sampled, also with aseptic instrumentation (sample numbers 33, 34, see Supplemen-

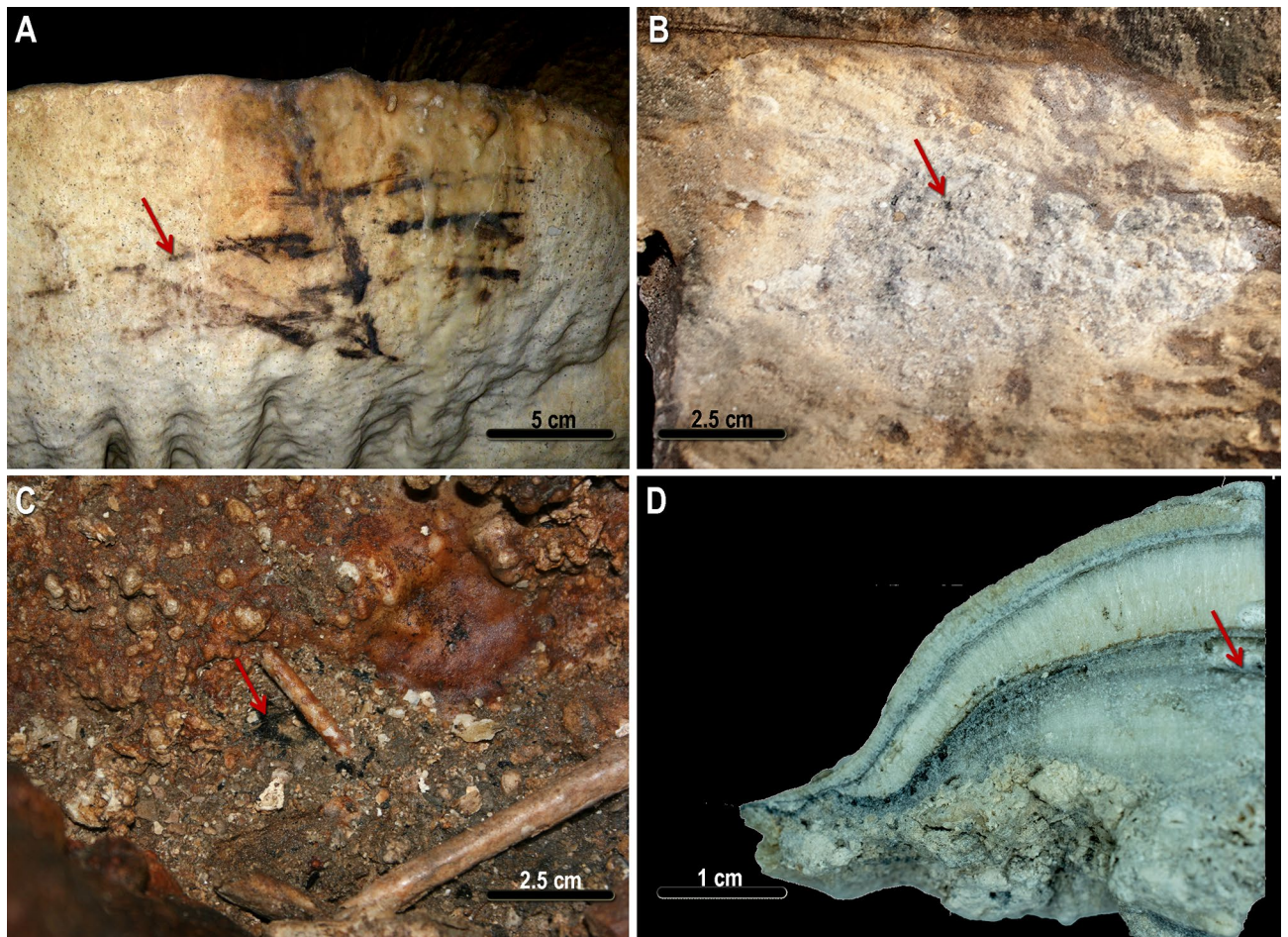


Figure 1. Image composition of the materials. (A) Black mark (dating number 33). (B) Micro-charcoal inside fixed lamp (dating number 43). (C) Scattered charcoals (dating number 54). (D) GN16-08 stalagmite section. The red arrows point to one of the samples, analysed both by TEM–EDX and Raman micro-spectroscopy.

ary information (S2) (Fig. 1A). These black marks correspond to the numbers 265 and 284 of the cave art catalogue⁷ and their dating was previously published by some of us¹⁷.

- (c) *Stalagmite with soot microlayers* A 9 × 3.5 cm high stalagmite was collected in the Cataclysm room. For the study of its internal structure, the stalagmite was sectioned into four quarters. To characterize the soot, Raman analysis was performed on several of the black micro-levels present in its internal structure, as well as TEM–EDX analysis of a sample powder extracted by scraping with a scalpel from lower black microlayers of the stalagmite (Fig. 1D).

Results

The Bayesian model for the internal rooms of Nerja cave, through radiocarbon dating on charcoal, includes 53 results, as 15 of them did not pass the validity analysis. There are several samples that were dated before their identification. Therefore, for these few samples, we cannot confirm that they correspond to organic residues of prehistoric underground activities (samples 1–10, 20–21, 67–68). Other samples were excluded because they were linked to the contemporary use of the cave (samples 1–10), as well as one date that shows a high deviation (sample 64), which could hinder the precise chronological identification of their respective phases.

In Supplementary information (S2) we have included the results of all ¹⁴C datings on charcoal (not only those implemented in the Bayesian model) and additional information about the nature and the localization of the samples inside the cave. Twenty-seven samples were characterised as “indeterminate charcoal”, 15 as “*Pinus tp. sylvestris-nigra*”, 1 as “*Pinus tp. cf. pinea-pinaster*”, 3 as “*Pinus sp.*” and 5 as “conifer”. The predominant characterization as “indeterminate charcoal” is due to the high presence of charcoal with a strongly altered structure in relation to the presence of vitrification, the surface exposure of most of the remains (trampling, hyperfracturing, etc.) and the small size of some samples.

The Bayesian model suggests at least 12 distinct phases of visits to the interior of Nerja cave between 41,218 and 3299 cal BP, with an agreement index (Aoverall) of 98 (see Supplementary information S4–S5 for more information). These phases of visits to the interior of the cave correspond to the specific chronocultural periods for the prehistoric regional context and with transitional periods: Early Aurignacian (phase 1), Recent Aurignacian (phase 2), Gravettian (phase 3), Lower Solutrean (phase 4), Middle Solutrean (phase 5), Upper Solutrean (phase

6), transition between the Upper Solutrean and Lower Magdalenian, and Lower Magdalenian (phase 7), Middle Magdalenian (phase 8), Upper Magdalenian (phase 9), Early Neolithic (phase 10), Recent Neolithic (phase 11) and Copper Age (phase 12). For the start and end dates of each phase see Supplementary information S5, table rows “Boundary Start Phase” and “Boundary End Phase” (Fig. 2).

There are 12 possible transition intervals between the different phases. One of them, separating phases 9–10 (between the Upper Magdalenian and the Early Neolithic), has a notable chronological amplitude (> 6000 years). At the same time, there are 8 transition periods that could correspond to 0 years (almost-continuous phases, taking into account the minimum values), in particular, those between phases 1–2 (both could be included in the Aurignacian, the former probably belonging to the ancient phase and the latter to the evolved stage), 4–5 (between the Lower Solutrean and the Middle Solutrean), 5–6 (between the Solutrean and the Middle Solutrean), 6–7 (around the Upper Solutrean and the transition between the Upper Solutrean and Lower Magdalenian), 7–8 (between the Lower Magdalenian and Middle Magdalenian), 8–9 (between the Middle Magdalenian and Upper Magdalenian), 10–11 (between the Early Neolithic and Recent Neolithic), and 11–12 (between the Recent Neolithic and Chalcolithic). In these quasi-continuous periods the term “phase” is debatable. However, we have taken into account the average values for the identification of transitional periods, which in no case is 0. For Interval Transition Phases see (Supplementary information S5-, table rows “Interval Transition Phases”) (Fig. 2).

The chronology of the soot microlayers found in the GN16-08 stalagmite was determined by the analysis of CaCO_3 layers deposited before and after them. The soot microlayers at the base of the stalagmite were deposited between 7562 and 6736 cal. BP (0% DCP); the soot microlayers from the upper level of the stalagmite were deposited between 6836 and 2998 cal. years BP assuming 0% of DCP (see Supplementary information S6 for more information).

In the Raman spectra carried out on the soot levels, the D and G bands typical of carbon bounds in polycyclic carbonaceous materials can be recognised, together with a peak at 1085 characteristic of carbonates^{18,19}. TEM–EDX observations revealed spherical carbon particles of soot aggregates similar to those found in Domica cave (Slovakia)²⁰. In Nerja Cave, similar particles were observed inside a Palaeolithic fixed lamp in the upper

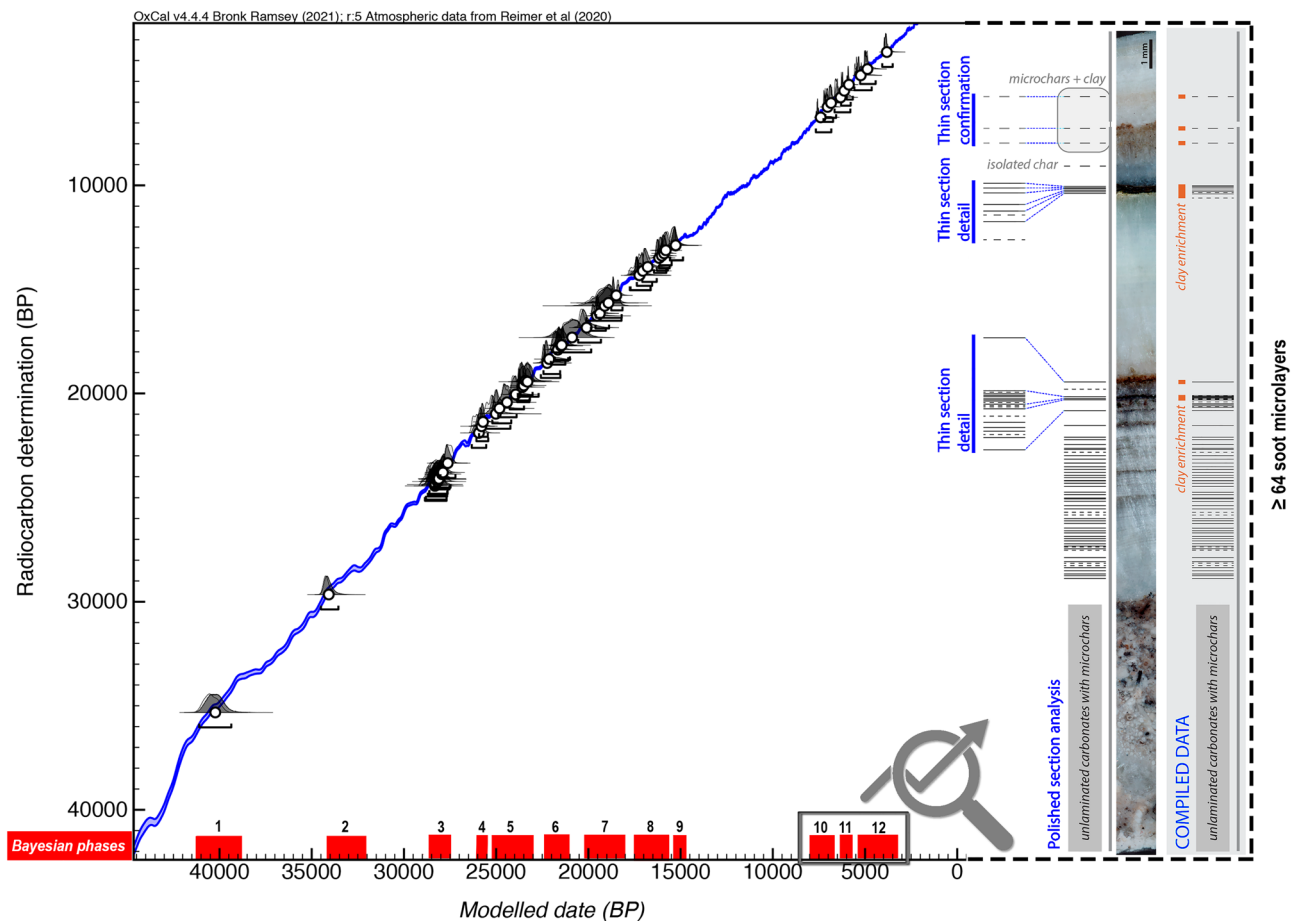


Figure 2. Curve plot with the different phases of visits to the interior of Nerja cave identified by a Bayesian model from charcoal (in red) and image of the different micro-layers of soot and micro-charcoal of the GN16-08 stalagmite, which increase the minimum number of occupations to at least 64 for the last 3 Bayesian phases. The succession of soot films in the carbonates is represented as barcode diagrams. Bars represent soot films and dashed lines represent probable soot films. The long vertical grey line next to the barcode represents speleothem total thickness.

galleries¹³, but soot residues were also located in another speleothem fragment inside the cave^{21,22}. Microscopic observation revealed that clay deposits were only associated with the microcharcoal or soot levels, suggesting that clay was not brought in by percolation at different times of the stalagmite formation but that the human visits to the cave contributed to the suspension of clays that re-deposited in the stalagmite. Our interdisciplinary analyses (Optical Microscopy, Raman and TEM-EDX) confirm that the black levels observed in stalagmite GN16-08 are the result of particulate emissions from wood combustion, mainly composed of concentric nanoparticles of soot²⁶, sometimes including also microcharcoal and occasionally clay re-deposited during human occupations (see Supplementary information S7).

The fuliginochronological analysis^{23–25} of the internal structure of this stalagmite allowed us to identify a minimum of 64 occupations (a Minimum Number of Occupations—MNO that can be increased to 82 if we also count uncertain soot films and microcharcoal alignments. This second case will be included in brackets from now on) (see supplementary information S7 for more information) (Fig. 2). If we relate these data to the phases determined by Bayesian analysis, we can state that at least 58 (71) different occupations occurred in phases 10 and 11 (Early Neolithic and Recent Neolithic) with no apparent hiatus between these two phases (a result that is consistent with the Bayesian model from charcoal), and at least 6 (8) visits in phase 12 (Copper Age).

Based on the duration in years of each phase (Internal duration) obtained by the Bayesian model (Supplementary information S5), and correlating these data with the microcount of the soot microlayers and their respective CaCO₃ dating, we suggest that between the Early Neolithic and the Recent Neolithic (phases 10 and 11) there was an average of one visit inside the cave every 35 years (if we consider the average chronological values; it is also possible that these Holocene visits occurred continuously over a certain period of time). This level of precision by the study of underground prehistoric activity is pioneering and clearly shows the potential of the applied methodology, and the importance of Nerja cave as a site for the study of the use of caves during prehistoric times.

The spatial distribution of the studied samples (Fig. 3) indicates that the Lower Galleries of Nerja cave (Cascade Room and Cataclysm Room) are the sectors with the highest number of distinct visits; they evidence 12 phases, between 41,336 to 4604 cal. BP, including the last three phases of the Bayesian model (Early Neolithic, Recent Neolithic and Copper Age) which can be broken down into at least 64 distinct visits according to the soot micro-layers. These are the sectors closest to the present and prehistoric entrances, which are currently prepared for tourist visits. However, without the recent modifications (stairs, walkways, widening of narrow passages, etc.) the topography of these galleries may have been very complicated, with very difficult obstacles (vertical passages, holes, ledges, narrow passages, etc.) and a speleological development of more than 1 km with continuous topographical features. Most of the dated samples from this area were located in various peripheral sectors with Palaeolithic art from the Cataclysm Room, with the exception of two samples from phases 11 (Recent Neolithic) and 12 (Copper Age), which were collected in the Cascade Room, next to a *Pecten* sp. shell that might have functioned as a mobile lamp¹⁵.

The 64 incursions detected through the fuliginochronological study also correspond to visits to the Lower Galleries of the cave, and in particular to a peripheral and elevated room known as “Plataforma Raspador”, which is a platform of about 47 m² where there are projections of red pigmentation on the west wall. In addition to the 64 phases relating to the Holocene chronology, the Bayesian phases 8–6 (Upper Solutrean, transition between the Upper Solutrean and Lower Magdalenian, Lower Magdalenian, and Middle Magdalenian) have been found in this particular sector of the cave. Therefore, the recurrence of visitation phases can be traced back to specific areas of the cave.

The Upper Galleries of the cave host the deepest areas of the cavity (a distance of between 1 and 4.8 km from the entrance), and are separated from the Lower Galleries by a very difficult speleological obstacle (a vertical wall of more than 30 m that can only be climbed by a steep and dangerous path, with narrow passages and small ascents of 7 m or less). These extremely difficult areas to access were visited since the beginning of Phase 4, from the Lower Solutrean, around 26,188 cal BP. All successive phases of visits up to Recent Prehistoric times are recorded here, with the exception of phases 8–9 relating to the Middle Magdalenian and Upper Magdalenian, respectively. In addition, other dates were obtained in these deep sectors (including chronologies from the Mousterian, as well as the Epipalaeolithic), although they did not pass the validity filter and thus remain, for the time being, unconfirmed phases for the internal occupation of the cave.

Phases 5 and 6, corresponding to the Middle Solutrean and Upper Solutrean periods (25–21,000 cal BP), appear to be the periods in which the anthropization of the cave was the most expansive in terms of spatial extension, ranging from the entrance rooms to the Immensity Room (more than 3 km from the outside). Furthermore, this incursion into the deep underground environment is the oldest known to date. In contrast, the least spatially developed periods of prehistoric visits to the interior of the cave took place in the early (< 3: Aurignacian and Gravettian) and late Upper Palaeolithic (8–9: Middle and Upper Magdalenian) phases, which are limited to the Lower Galleries (Cataclysm Room).

Discussion

Currently, Nerja Cave is the Palaeolithic Art cave in Europe where the greatest number of phases of distinct prehistoric visits to internal areas have been recorded, making it a unique and exceptional place for understanding the recurrent use of the subterranean environment during prehistoric times.

The Bayesian analysis, including ¹⁴C dating from charcoal, confirmed the hypothesis of the existence of at least 12 distinct visitation phases between the Aurignacian and the Copper Age (41,218–3299 cal BP). The study of the soot levels present in a Holocene stalagmite made it possible to reach a higher degree of precision for the last three phases, relating to the Early Neolithic, Middle-Final Neolithic and Copper Age (8003–3299 cal BP), increasing the minimum number of incursions to 64 for this period. In total, at least 73 phases of distinct visits to the interior of the cave between the Upper Palaeolithic and Recent Prehistory have been recorded.

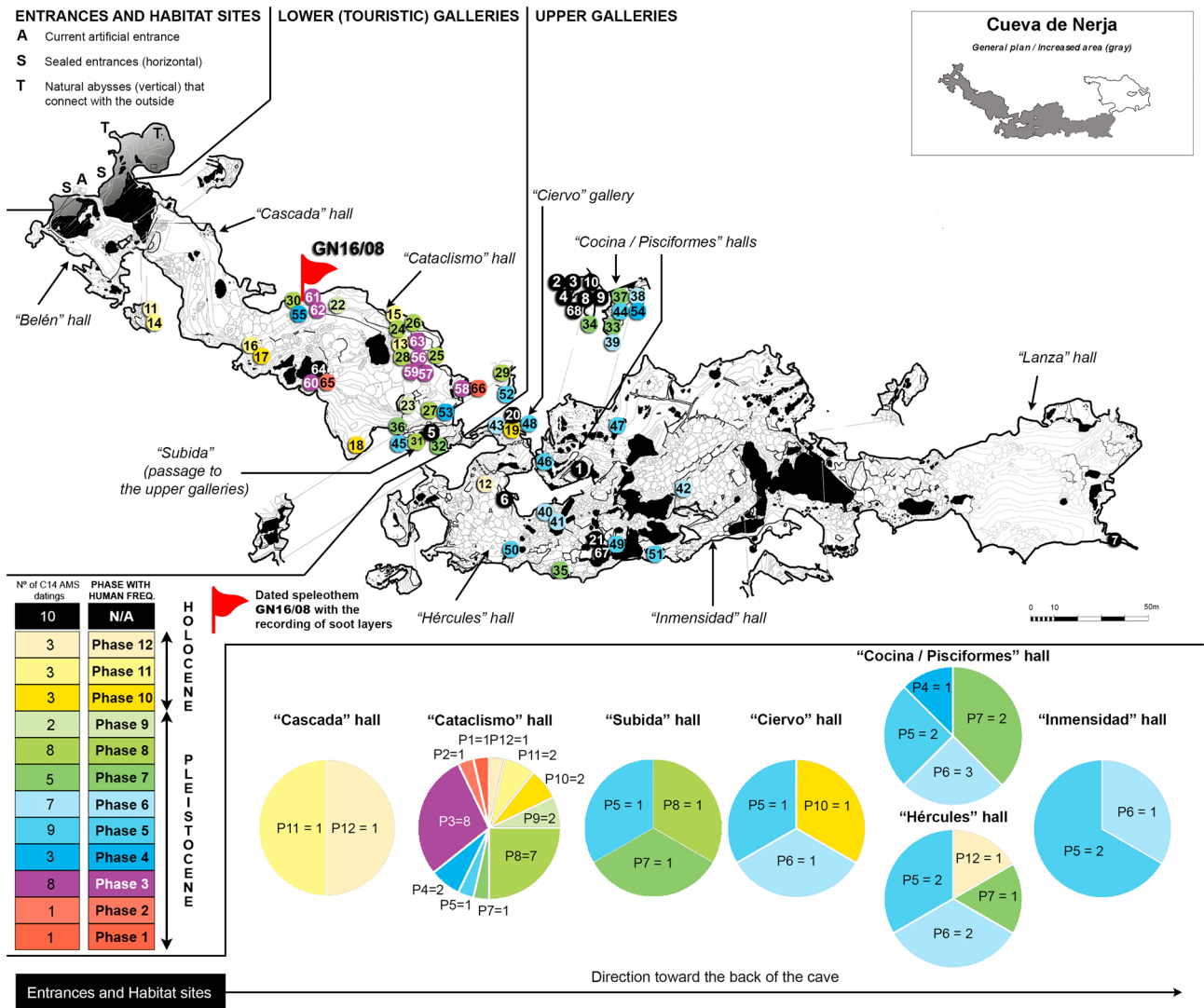


Figure 3. Planimetry of Nerja cave with the location of the analysed samples (modified from Medina-Alcaide 2019²⁷). Circles indicate the charcoal samples dated by ¹⁴C, and the red flag marks the place of the stalagmite GN16-08 with the micro-levels of soot. The colour of the circles corresponds to the Bayesian phases from charcoal dating. In the lower right part of the image, the number of phases is represented by means of circle graphs for each room of the cave. Specific information about each sample can be found in “Supplementary Materials”. The numbers in the circles correspond to the number of samples.

Furthermore, this work extends the origin of the prehistoric occupation of the Nerja cave by 10,000 years. The archaeological and chronometric analysis of the sedimentary deposits present in the entrance areas of the cave confirmed an extensive period of use of the cave between 30,000 and 4000 years, encompassing the Gravettian, Lower Solutrean, Middle-Upper Solutrean, Upper Magdalenian, Epipalaeolithic, Mesolithic, Early Neolithic, Middle-Recent Neolithic and Chalcolithic chronocultures²⁻⁶. Our study of the internal areas of the cave allowed us to extend the periods of occupation recorded in the cave, identifying for the first time two phases of visits relating to the Aurignacian period, namely phases 1 and 2 (Early Aurignacian and Recent Aurignacian), the former corresponding to the Early Aurignacian and the latter to the Evolved Aurignacian.

The oldest date included in the Bayesian analysis (dating 66) is difficult to classify in a specific technocomplex, since in the stratigraphic sequences of the external rooms of the cave there are no such old dates, and at the regional level there is no consensus for the end of the Middle Paleolithic and the beginning of the Upper Paleolithic²⁸⁻³². Therefore, and with the data available today, we could relate this date to some transitional moment between the Middle and Upper Paleolithic. As for the dating 65, this could fit with the recent Aurignacian. This is a period that has already been detected in the east of the Iberian Peninsula with occupations that include the characteristic industry and personal ornamentation³³⁻³⁹. This second dating would be one of the few evidences of recent Aurignacian in the south of the Iberian Peninsula, coeval with the recently published dates obtained in a sector near the prehistoric entrance of the Ardales cave⁴⁰ (Supplementary information S8).

Cross dating (¹⁴C and U/Th) of CaCO₃ layers covering red dots established that these pictorial elements could be made before 25,370–25,000 cal BP (*terminus ante quem*)⁴¹, that is, at some time between phases 1–5 defined

by the Bayesian model (Early Aurignacian -phase 1-, Recent Aurignacian -phase 2-, Gravettian -phase 3-, Lower Solutrean -phase 4- and Middle Solutrean -phase 5). Thus, at least part of the red-coloured paleolithic art found in the Lower Galleries, mostly composed of simple signs (such as dots, and probably also, paired lines, lines...) could be made between these first occupation phases.

Likewise, certain palaeolithic figures that accompany these simple signs in the Lower Galleries of the cave are thought to correspond to this pre-Magdalenian chronology from a chronostylistic point of view. For example, the figures of hinds in these galleries that have a trilinear convention and/or an exaggerated projection of the necks of some animals link better with phases 3–4 (Gravettian, Lower Solutrean and Middle Solutrean). Furthermore, the horses with the “duck-beak” convention present in this part of the cave could be linked to phase 4 (Middle Solutrean), based on the direct dating of a similar motif in La Pileta cave (Andalusia, Spain)⁴² and the preferential location of these motifs on the plaquettes from this period in the Parpalló cave (Valencia, Spain)⁴³.

The occupation phases 6–7 (Upper Solutrean—transition between the Upper Solutrean and Lower Magdalenian), could be related to motifs ascribed to the Advanced Solutrian from a stylistic and formal perspective⁷. Likewise, occupation phase 7 (Lower Magdalenian) could be related to the execution of the black marks; in fact, of the five dates that are grouped together in this period, two correspond to direct dating dates of this type of parietal marks¹⁷.

Additionally, for the first time in Nerja Cave, the presence of visits that can be chronologically placed in the Lower Magdalenian (phase 7) and Middle Magdalenian (phase 8) has been confirmed. In the sedimentary sequences of the entrance rooms of this cave, this episode coincides with an erosive process that probably dismantled part of the archaeological sequence, explaining its absence^{2,5}. Thus, we suggest that the new dates presented in this work, relating to the Lower Magdalenian period, support a continuity of occupation in Nerja cave, and therefore in the south of the Iberian Peninsula, between the Solutrian and Magdalenian periods. In this respect, it is worth highlighting the suitability of the chronological study of the Internal Archaeological Context to strengthen and extend the sequence of use of the caves, as the archaeological remains are generally located beyond the reach of erosive processes that most often take place in the external areas of caves.

Most of the radiocarbon datings presented in this work are related to the different visits to the interior of the cave. Only dates n.33 and n.34 correspond to direct results from the pigment of certain palaeolithic motifs, in particular non-figurative black marks (phase 7-Lower Magdalenian). Therefore, the results of this work alone cannot be used to date the Palaeolithic Art of the interior of Nerja cave. However, we consider that these data can be used to build arguments about the chronology of the different uses of the cave (only one of them being the execution of the graphic manifestations), together with other chronometric, archaeological and/or stylistic data. For example, the absence of carbons of Aurignacian, Gravettian or Middle and Upper Magdalenian chronology in the Upper Galleries of the cave suggests that most probably the visits to these areas (including the one(s) linked to the artistic execution) do not correspond to these periods, and that therefore, the pictorial activity at this site could be related to some time(s) between the Early Solutrian and the Lower Magdalenian, as suggested by the indirect (and direct, in the case of the Lower Magdalenian) dating obtained in this area. In this argument, we must also consider that charcoal from these phases may not have been found, for example, due to taphonomic processes, because the activity was limited in these areas or that the remains may have been destroyed by later occupations.

The Occupation phase 9 (Upper Magdalenian) does not seem to be linked to the execution of Palaeolithic art inside the cave, at least according to the chrono-stylistic data currently available for the cave's rock art. Following some chrono-stylistic parallels, the pisciform pictures of the Upper Galleries have been attributed to the Upper Magdalenian⁷, but the chronocultural ascription of this pictorial group is controversial and is still an open question today^{22,44}. For the Upper Magdalenian, although we did not find clear evidence of rock art in the internal rooms of Nerja cave, portable figurative art was found in the archaeological deposits in the entrance rooms⁴⁵.

Finally, phases 10–12 (Early Neolithic, Recent Neolithic and Copper Age) could be related to the burial activities documented for these periods. These activities include the deposition of human skeletal remains, ceramics and/or personal ornaments^{11,46}. In this paper, we provide new chronological data on these incursions, which run from the Early Neolithic to the Copper Age, as well as information on their topographical distribution, preferably linked to the Lower Galleries, although two specific explorations of the upper parts of the cave were also identified (samples 12, 19). In other words, the visits concerning Recent Prehistory are not restricted to burial activities in the Lower Galleries, but are also due to exploratory actions, not to mention the execution of cave art linked to these dates and present in one of the external rooms (specifically, the schematic anthropomorphs in the Torca room). Furthermore, the confirmation, through the analysis of the micro-levels of soot present in the stalagmite, of at least 64 visits constitutes a real novelty for the understanding of the use of the subterranean environment during Recent Prehistory. In particular, between the Early Neolithic and the Recent Neolithic (phases 10 and 11) there was an average of one visit inside the cave every 35 years (considering average chronological values of 95.4% confidence intervals).

Dates 67 and 68, relating to an antiquity greater than 40,000 years old, are controversial dates, which deserve to be analysed in depth, as they imply significant interpretative changes for the Prehistory of the southern Iberian Peninsula. These samples were found at two different points in the Upper Galleries (in the Pisciform and Hercules rooms), in sectors located more than 1 km from the entrance and extremely difficult to access. Anthropoc occupation of the subterranean environment existed since at least the Middle Pleistocene (ca. 176,000 years BP), as attested by evidence located more than 300 m from the entrance in the Bruniquel cave (Aveyron, France). Evidence includes the use of lighting systems, necessary for subterranean appropriation, by Neanderthal groups, the geomorphological modification of space and the construction of structures using speleothems¹. The evidence from Nerja would be a significant novelty, as it would certify the ability of another ancient human species (*Homo neanderthalensis*), not only to frequent areas in total darkness and far from the entrance (as in the case of the Bruniquel cave), but also to overcome extremely difficult speleological obstacles inside caves.

These dates were among the first we made and were not subjected to anthracological analysis prior to dating, i.e. they were not subjected to microscopic study to confirm their anthropic origin. However, we do have $\delta^{13}\text{C}$ analysis of both samples (Supplementary information S2), one of which (dating 68), falls within the range for carbonised organic matter (-29 to 21%). As this parameter is generally used to assess fractionation during ^{14}C measurement, it is difficult, without an independent analysis apart from dating, to reach a conclusion. For all these reasons^{47–49}, we consider this result insufficient to accept (for the moment) these revolutionary dates; we also consider it essential to undertake other interdisciplinary analyses to definitively confirm or reject the existence of Middle Palaeolithic visits inside Nerja cave (Supplementary information S3). We therefore began the chronometric analysis of the carbonates associated with the parietal art of Nerja^{17,22,41,44}, which has offered novel methodological aspects on U/Th and ^{14}C dating, despite no conclusive data on the Neanderthal chronology of any of the graphic motifs located inside the Nerja cave.

On the other hand, we do not rule out the possibility that in the future the number of phases of visits will be extended, for example with phases of occupation related to the last hunter-gatherers (Epipalaeolithic phases), already recorded in the stratigraphic sequence of the entrance rooms and common in the internal areas of other caves decorated with Palaeolithic art (some of them in areas very far from the entrance and/or with very complicated access)^{50–54}. Nevertheless, and in the same way as for the previous case referring to the beginning of the visits from the Middle Palaeolithic, and although we have two dates that could testify to Epipalaeolithic visits (n. 20, 21), for the moment, we prefer not to take this information into account, as it did not pass the validity test to which we subjected all the dates before the Bayesian study (for more information, see Supplementary information S1, S2 and S3). It should also be remembered that our samples come from a particular context with no stratigraphic data to support the dates. Furthermore, the application of the analysis of soot levels on carbonate deposits of Palaeolithic chronology could extend the minimum number of visits. Previous studies confirmed the existence of carbonate formations for Palaeolithic chronology in Nerja Cave⁴¹, in particular thin calcium carbonate films on some paintings, so it would be possible to apply this state-of-the-art methodology to the Pleistocene occupation period as well.

In terms of the anthracological data obtained, “*Pinus tp. sylvestris-nigra*” is the most frequent taxonomic identification (if we exclude the general characterisation of “indeterminate charcoals”), not only in the charcoal samples dated from inside the cave, but also in all the samples examined in relation to the fuel used for lighting in Nerja cave^{12,13}. As already shown in previous studies, there is a repeated and almost exclusive use of this type of wood for cave raids and for lighting, especially during the Upper Palaeolithic. The environmental conditioning factor does not seem to be the main reason for this choice, because other species were available in the surroundings of the caves⁵⁵, and other reasons for this choice have been proposed, linked to functional purposes (due the benefits of these resinous woods for cave lighting) and even cultural ones^{56,57}.

Furthermore, thanks to the ^{14}C dating included in this work, following anthracological analysis, we have verified that the choice of *Pinus tp. sylvestris-nigra* wood for lighting-related activities in Nerja cave is not only a wood that is preferentially used compared to other types available in the environment (*Pinus tp. pinea-pinaster*, *Juniperus sp.*)^{12,54}, but also that it is not exclusive to a specific Palaeolithic phase or cultural period, but is a multiphasic selection. Specifically, the choice of this woody resource for lighting was recorded in 8 of the 9 Palaeolithic occupation phases documented in this work, between phases 2–9 (Gravettian—Upper Magdalenian) inclusive. Likewise, the repeated use over time of *Pinus sylvestris* for lighting has been previously proposed for the Chauvet cave, and for two different periods of occupation referring to the Aurignacian and Gravettian^{56,57}. The anthracological data from this study further reinforce this idea of a preferential and cross-cultural choice of *Pinus tp. sylvestris-nigra* for lighting activities inside caves during the Upper Palaeolithic.

Conclusions

In this work we carried out an interdisciplinary and chronometric study of different combustion residues (charcoal and microlayers of soot) located in the Internal Archaeological Context of Nerja cave. The charcoals are linked to the lighting systems used by prehistoric groups to enter the deep areas of the cave and were found mainly on the surface in the interior of the cave, although we also included in this work two samples of the carbonaceous pigment of two Palaeolithic signs. The ^{14}C dating of 53 of these charcoals, following anthracological analysis and after passing an ad hoc validation test and a subsequent Bayesian analysis, identified 12 phases of prehistoric visits to the interior of the cave between 41,218 and 3299 cal BP, and enabled us to define the periods between phases and the duration of each phase. This has allowed us to extend the general chronological interval of the site, pushing back the origin of human occupation in Nerja cave by more than 10,000 years, as well as to identify chrono-cultures hitherto unknown in the cave, such as the Aurignacian, Lower Magdalenian and Middle Magdalenian, some of which are very little known for the context of the southern Iberian Peninsula.

The interdisciplinary analysis of the microlayers of soot present in a stalagmite of Holocene chronology allowed us not only to robustly characterise this type of remains but also to carry out a high-precision zoom on the last three phases of visits identified through Bayesian analysis, proving that these three phases contain a minimum of 64 distinct incursions. Based on this analysis, we propose that between the Early Neolithic and the Recent Neolithic (phases 10 and 11) there could have been a visit to the interior of the cave every 35 years on average (without excluding another rate of occupation for this interval). This level of chronological precision for prehistoric archaeology is truly ground-breaking.

The prehistoric subterranean activities of Nerja cave are not only heterogeneous in terms of chronological diversity, but also in terms of spatial extension, showing moments of advance and regression in relation to the surface and depth throughout the different phases of prehistoric use and visits to the interior of the cave. The topographic analysis of the charcoal dated and the soot microlayers shows that not all the spaces in the cave were used in the same periods, with the reiteration of visits to the Cataclysm Room (Lower Galleries) or the Raspador

Platform (where the stalagmite was collected with the recorded soot layers), and the more restricted occupation of the Upper and deeper Galleries of the cave being particularly noteworthy.

A representative set of radiocarbon dates such as those presented in this work, linked to the combustion residues located in the deep areas of cavities with Palaeolithic Art, can offer information on the chronology of the art, although not in a direct or conclusive manner. This type of chronological information is useful as a complement to other data (archaeological, geomorphological, etc.), especially when direct dating of rock art is difficult to carry out, as it is made of inorganic material or, as in the case of some of the black paleolithic graphics of the Upper Galleries of Nerja cave, because the carbonised pigment is deeply embedded in the wall and impossible to sample using current techniques. The chronological determination of Palaeolithic art through indirect approaches is a complex task and it is essential to combine different methods and study strategies^{22,41}.

The data from the anthracological analysis, prior to the dating of the charcoals, point to a specific and transcultural use of *Pinus tp. sylvestris-nigra* for activities linked to the lighting of the cave, at least between the Gravettian and Upper Magdalenian periods, and not linked to environmental restrictions. It can therefore be concluded that the choice of this type of wood for incursions into caves is a transcultural and multiphase choice, at least during the time when this type of tree was available in the cave environment, and probably linked to the benefits of this type of resinous wood for lighting activities.

Overall, this work has demonstrated the potential of interdisciplinary and chronometric analysis of the Internal Archaeological Context, and in particular of charcoals and soot micro-levels linked to different prehistoric lighting systems, for a comprehensive understanding of the “lifespan” of a prehistoric cave.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files]. However, should any information that any researcher wishes to consult be missing, it will be made available through the corresponding author on reasonable request.

Received: 14 January 2023; Accepted: 29 March 2023

Published online: 11 April 2023

References

- Jaubert, J. *et al.* Early neanderthal constructions deep in Bruniquet Cave in southwestern France. *Nature* **534**, 111–115 (2016).
- Jordá, J. F. *et al.* Evolución paleogeográfica, paleoclimática y paleoambiental de la costa meridional de la Península Ibérica durante el Pleistoceno superior. El caso de la Cueva de Nerja (Málaga, Andalucía, España). *Bol. Real Soc. Esp. Hist. Nat.* **105**, 137–147 (2011).
- Jordá, J. F. & Aura, J. E. 70 fechas para una cuevac Revisión crítica de 70 dataciones C14 del pleistoceno superior y holoceno de la cueva de nerja (Málaga, Andalucía, España). *Esp. Tiempo Forma* **1**, 239–256 (2008).
- Simón, M. D., Liñán, C., del Rosal, Y. & Marín, F. Investigaciones en la cueva de Nerja. 1959–2004, in *Cuevas Turísticas: Aportación al Desarrollo Sostenible*, 31–39 (Instituto Geológico y Minero de España, 2007).
- Jordá, J. F. & Aura, J. E. Radiocarbono, cronoestratigrafía y episodios ocupacionales en el Pleistoceno superior y Holoceno de la Cueva de Nerja (Málaga, Andalucía, España), in *Zona Arqueológica 7 (Miscelánea en Homenaje a Victoria Cabrera vol. 1)* 579–595 (Museo Arqueológico Regional, Comunidad de Madrid, 2006).
- Sanchidrián, J. L. & Márquez, A. M. Primeros resultados de la secuencia crono-estratigráfica de la Sala de la Torca de la Cueva de Nerja (Málaga, España). In *La cuenca mediterránea durante el Paleolítico Superior: 38.000–10.000 años* (eds Sanchidrián, J. L., Márquez, A. M. & Fullola, J. M.) 272–283 (U.I.S.P.P. y Fundación Cueva de Nerja, 2005).
- Sanchidrián, J. L. *Arte Rupestre de la Cueva de Nerja*. (Fundación Cueva de Nerja, 1994).
- Medina-Alcaide, M. Á., Garate, D., Ruiz-Redondo, A. & Sanchidrián, J. L. Beyond art: The internal archaeological context in Paleolithic decorated caves. *J. Anthropol. Archaeol.* **49**, 114–128 (2018).
- Clottes, J. Contexte archéologique interne, in *L'Art pariétal Paléolithique. Techniques et méthodes d'étude* (ed. G.R.A.P.P.) 49–58 (CTHS, 1993).
- Medina-Alcaide, M. Á. *et al.* Alterations anthropiques du paysage souterrain dans la grotte de Nerja au Paléolithique supérieur. Oral communication in *XXIIIe colloque du GMPCA: Archéométrie 2022*, 02–06 mai 2021 Chambéry (France, 2022).
- Pellicer, M. & Acosta, P. Síntesis: El neolítico y calcolítico en andalucía. In *El Neolítico y Calcolítico de la Cueva de Nerja en el contexto andaluz* (eds Pellicer, M. & Acosta, P.) 373–393 (Patronato de la Cueva de Nerja, 1997).
- Medina-Alcaide, M. Á., Sanchidrián, J. L. & Zapata, L. Lighting the dark: Wood charcoal analysis from Cueva de Nerja (Málaga, Spain) as a tool to explore the context of Palaeolithic rock art. *C.R. Palevol* **14**, 411–422 (2015).
- Medina-Alcaide, M. Á. *et al.* Multianalytical and multiproxy approach to the characterization of a Paleolithic lamp. An example in Nerja cave (Southern Iberian Peninsula). *J. Archaeol. Sci. Reports* <https://doi.org/10.1016/j.jasrep.2019.102021> (2019).
- Medina, M. Á., Cristo, A., Romero, A. & Sanchidrián, J. L. Otro punto de luz. Iluminación estática en los “santuarios” paleolíticos: El ejemplo de la Cueva de Nerja (Málaga, España). *Préhist. Art Soc. Bull. Soc. Préhist. l'Ariège* **65–66**, 105–121 (2012).
- Medina-Alcaide, M. Á. Indicios de iluminación prehistórica en el contexto arqueológico interno de las cuevas decoradas: Tipos y potencial arqueológico. In *En torno al arte: El contexto arqueológico interno de las cuevas decoradas. Actas XIX International Rock Art Conference IFRAO* (eds Collado, H. & García-Arranz, J. J.) 505–510 (Arkeos, 2015).
- Medina-Alcaide, M. Á. *et al.* The conquest of the dark spaces: An experimental approach to lighting systems in Paleolithic caves. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0250497> (2021).
- Sanchidrián, J. L., Valladas, H., Medina-Alcaide, M. Á., Pons-Branchu, E. & Quiles, A. New perspectives for 14C dating of parietal markings using CaCO₃ thin layers: An example in Nerja cave (Spain). *J. Archaeol. Sci. Rep.* **12**, 74–80 (2017).
- Martínez-Ramírez, S. *et al.* Micro-Raman spectroscopy applied to depth profiles of carbonates formed in lime mortar. *Cem. Concr. Res.* **33**, 2063–2068 (2003).
- Sadezky, A., Muckenhuber, H., Grothe, H., Niessner, R. & Pöschl, U. Raman microspectroscopy of soot and related carbonaceous materials: Spectral analysis and structural information. *Carbon* **43**, 1731–1742 (2005).
- Pawlyta, M. & Hercman, H. Transmission electron microscopy (TEM) as a tool for identification of combustion products: Application to black layers in speleothems. *Ann. Soc. Geol. Pol.* **86**(2), 237–248 (2016).
- Del Rosal, Y. R. *Análisis, impacto y evolución de biofilms fotosintéticos en espeleotemas. El caso de la Cueva de Nerja*. (PhD Tesis. Universidad de Málaga, 2016).
- Pons-Branchu, E. *et al.* U-series and radiocarbon cross dating of speleothems from Nerja Cave (Spain): Evidence of open system behavior Implication for the Spanish rock art chronology. *Quat. Sci. Rev.* <https://doi.org/10.1016/j.quascirev.2022.107634> (2022).

23. Vandeveldel, S., Brochier, J. É., Petit, C. & Slimak, L. Establishment of occupation chronicles in Grotte Mandrin using sooted concretions: Rethinking the Middle to Upper Paleolithic transition. *J. Hum. Evol.* **112**, 70–78 (2017).
24. Vandeveldel, S., Brochier, J. É., Desachy, B., Petit, C. & Slimak, L. Sooted concretions: A new micro-chronological tool for high temporal resolution archaeology. *Quat. Int.* **474**, 103–118 (2018).
25. Vandeveldel S. *Y'a Pas de Suie Sans Feu ! Étude Micro-chronologique des Concrétions Fuligineuses. Étude de Cas: Le Site Paléolithique de la Grotte Mandri (France)*. (PhD thesis. Université Paris 1 Panthéon-Sorbonne (2019).
26. Kocbach, A. *et al.* Physi-chemical characterisation of combustion particles from vehicle exhaust and residential wood smoke. *Part. Fibre Toxicol.* **3**(1), 1–10 (2006).
27. Medina-Alcaide M.A. *Iluminando la Oscuridad de Las Cuevas Con Manifestaciones Gráficas Paleolíticasuna Visión Integral e Interdisciplinar del Contexto Arqueológico Interno y de Los Carbones de Madera*. Doctoral thesis. University of the Basque Country (UPV/EHU) (2019).
28. Cortés, M. *et al.* An early Aurignacian arrival in southwestern Europe. *Nat. Ecol. Evol.* **3**(2), 207–212 (2019).
29. Anderson, L., Reynolds, N. & Teyssandier, N. No reliable evidence for a very early Aurignacian in Southern Iberia. *Nat. Ecol. Evol.* **3**(5), 713–713 (2019).
30. De la Peña, P. Dating on its own cannot resolve hominin occupation patterns. *Nat. Ecol. Evol.* **3**(5), 712–712 (2019).
31. Cortés, M. *et al.* Reply to 'Dating on its own cannot resolve hominin occupation patterns' and 'No reliable evidence for a very early Aurignacian in Southern Iberia'. *Nat. Ecol. Evol.* **3**(5), 714–715 (2019).
32. Zilhão, J. *et al.* Precise dating of the Middle-to-Upper Paleolithic transition in Murcia (Spain) supports late Neandertal persistence in Iberia. *Heliyon* **3**(11), e00435 (2017).
33. Zilhão, J. The earliest upper paleolithic of southern and western Iberia is an evolved, not an early aurignacian, in *Côa Symposium. Novos olhares sobre a Arte Paleolítica/New perspectives on Palaeolithic Art* 52–71 (Associação dos Arqueólogos Portugueses/Fundação Côa-Parque, 2021).
34. Zilhão, J. Everything you always wanted to ask about the Lapa do Picareiro Aurignacian and should not be afraid to know: A reply to 'The early Aurignacian at Lapa do Picareiro really is that old'. *Quat. Sci. Rev.* <https://doi.org/10.1016/j.quascirev.2021.107296> (2022).
35. Iturbe, G. *et al.* Cova beneito (Muro, Alicante): Una perspectiva interdisciplinar. *Recer. Mus. d'Alcoi* **2**, 23–88 (1993).
36. Villaverde, V. *et al.* The early upper palaeolithic of cova de les cendres (Alicante, Spain). *Quat. Int.* **515**, 92–124 (2019).
37. Villaverde, V. *et al.* Cova de les Malladetes (Valencia, Spain): New insights about the early upper palaeolithic in the mediterranean basin of the Iberian Peninsula. *J. Paleolit. Archaeol.* **4**(1), 1–65 (2021).
38. Pascual, J. L. Industria ósea sobre huesos y dientes de lince en la prehistoria de la Península Ibérica. In *Interaccions Entre Felins i Humans: Homenatge a Innocenci Sarrión Montañana* (eds Sanchis, A., Pascual, J. L. & Sarrión, I) 189–212 (Museo de Prehistoria de Valencia, 2017).
39. Zilhão, J. *et al.* Precise dating of the Middle-to-Upper Paleolithic transition in Murcia (Spain) supports late Neandertal persistence in Iberia. *Heliyon* <https://doi.org/10.1016/j.heliyon.2017.e00435> (2017).
40. Ramos-Muñoz, J. *et al.* The nature and chronology of human occupation at the Galerías Bajas, from Cueva de Ardales, Malaga, Spain. *PLoS ONE* <https://doi.org/10.1371/journal.pone.0266788> (2022).
41. Valladas, H. *et al.* U/Th and 14C crossdating of parietal calcite deposits: Application to Nerja Cave (Andalusia, Spain) and future perspectives. *Radiocarbon* **59**, 1955–1967 (2017).
42. Sanchidrián, J. L. & Valladas, H. Dataciones numéricas del arte rupestre de la cueva de La Pileta (Málaga Andalucía). *Panel* **1**, 104–105 (2001).
43. Villaverde, V. *Arte paleolítico de la Cova del Parpalló: Estudio de la colección de plaquetas y cantos grabados y pintados* (Diputación de Valencia, Valencia, 1994).
44. Pons-Branchu, E. *et al.* U-series dating at Nerja cave reveal open system. Questioning the Neanderthal origin of Spanish rock art. *J. Archaeol. Sci.* <https://doi.org/10.1016/j.jas.2020.105120> (2020).
45. Márquez, A. M. Análisis tecnológico de una pieza de Arte mueble de la cueva de Nerja (Málaga, España). *Zephyrus* **58**, 135–158 (2005).
46. Fernández-Rodríguez, L. E. *La cuna del Megalitismo, Vida y Muerte en la Cueva de Nerja*. Microdocumental: Instituto de Investigación Cueva de Nerja. <https://www.youtube.com/watch?v=LF2ss2hhJDE> (consulted 27–09–2022) (2018).
47. Jouve, G. Utilisation des isotopes stables pour l'identification de l'origine du carbone dans la datation du charbon de bois du Paléolithique. *Anthropologie* **117**(4), 413–419 (2013).
48. Fontugne, M. *et al.* De l'utilisation des isotopes stables du carbone dans la datation par la méthode du radiocarbone. *Anthropologie* **118**(2), 194–200 (2014).
49. Audiard, B. *et al.* $\delta^{13}\text{C}$ referential in three *Pinus* species for a first archaeological application to Paleolithic contexts: "Between intra-and inter-individual variation and carbonization effect". *J. Archaeol. Sci. Rep.* **20**, 775–783 (2018).
50. Leroi-Gourhan, A. & Evin, J. Les datations de Lascaux. In *Lascaux Inconnu* (eds Leroi-Gourhan, A. & Allain, J.) 81–84 (Centre National de la Recherche Scientifique, Paris, 1979).
51. Clottes, J. & Simonnet, R. Retour au réseau clastres (Niaux Ariège). *Préhist. Ariégeoise* **45**, 51–139 (1990).
52. Barbaza, M. Premières datations ^{14}C des niveaux archéologiques de la galerie Vidal, grotte de Bédailhac (Ariège). *Bull. Soc. Préhist. l'Ariège* **52**, 33–43 (1997).
53. Ambert, P. *et al.* Les gravures et les empreintes humaines de la grotte d'Aldène (Cesseras-Hérault) dans leur contexte chronologique et culturel. *Bull. Mus. d'Anthropol. Préhist. Monaco* **47**, 3–36 (2007).
54. Dachary, M., Plassard, F. & Valladas, H. La grotte de Rouffignac (Dordogne, France): Un gîte de matière première exploité au Mésolithique. *Paleo. Rev. D'archéol. Préhist.* **27**, 133–148 (2016).
55. Badal, E. La végétation du Paléolithique supérieur et de l'Épipaléolithique aux alentours de la Cueva de Nerja. *Actes Coll. Périgues 1995. Suppl. Rev. d'Archéol.* 171–176 (1996).
56. Théry-Parisot, I. & Thiébaud, S. L. Pin (*Pinus sylvestris*): Préférence d'un taxon ou contrainte de l'environnement? Étude des charbons de bois de la grotte Chauvet. *Bull. Soc. Préhist. Fr.* **102**(1), 69–75 (2005).
57. Théry-Parisot, I. *et al.* Illuminating the cave, drawing in black: Wood charcoal analysis at Chauvet-Pont d'Arc. *Antiquity* **92**(362), 320–333 (2018).

Acknowledgements

This work is part of M. Medina's postdoctoral research project funded by the FYSSEN FOUNDATION (2021–2022). This research is also part of the "Proyecto General de Investigación aplicada a la conservación de Cueva de Nerja" authorised by the Junta de Andalucía and financed by the Fundación de Servicios Cueva de Nerja. This paper is also part of the following projects: a) A-Light project (PI M. Medina) (2022–2024), within the framework of HORIZON-MSCA-2021-PF-01-01 (project number 101066376), funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for them. This research also benefited from the scientific framework of the University of Bordeaux's

IdEx “Investments for the Future” program/GPR “Human Past”; b) Datations croisées uranium-thorium, uranium-protactinium et carbone-14 de carbonates secondaires en grottes: recherche de critères de validation des échantillons et des âges : Application à l’art pariétal led by H. Valladas and funded by ANR (France) (Grant Number ANR-18-CE27- 0004, ApART project); c) PID2019-107262GB-I00 “Before art: social investment in symbolic expressions during the Upper Palaeolithic in the Iberian Peninsula” (PI Diego Garate) funded by MCIN/AEI/10.13039/501100011033 (Spanish Ministry of Science, Innovation and Universities); d) PID2021-125166OB-I00, “ARTMINDHUMAN: creación y percepción en los humanos anatómicamente modernos: análisis de las capacidades biológicas, cognitivas y sociales ligadas a la producción del Arte Paleolítico” funded by MCIN/AEI (Spain) e) PID2021-126937NB-I00 (PALEOCROSS), funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe”; f) I. Intxaurbe’s PhD research is funded by the grant PIF 19/196 (2019) at the University of the Basque Country (UPV/EHU). We also thank the radiocarbon team of the Laboratoire des Sciences du Climat et de l’Environnement (CNRS/CEA/UVSQ/ Univ. Paris Saclay) as well the as the LMC14 staff (Laboratoire de Mesure du Carbone-14), ARTEMIS national facility, LSCE UMR 8212, for the results obtained with the Accelerator Mass Spectroscopy method.

Author contributions

M.M.-A. wrote the main manuscript text, M.M.-A. prepared Figs. 1, 2, S.V. prepared Fig. 2, I.I. prepared Fig. 3. All authors intensive reviewed the manuscript in several occasions.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-023-32544-1>.

Correspondence and requests for materials should be addressed to M.Á.M.-A.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2023