ANTHROPOLOGY

The earliest basketry in southern Europe: Hunter-gatherer and farmer plant-based technology in Cueva de los Murciélagos (Albuñol)

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Plant material culture can offer unique insights into the ways of life of prehistoric societies; however, its perishable nature has prevented a thorough understanding of its diverse and complex uses. Sites with exceptional preservation of organic materials provide a unique opportunity for further research. The burial site of Cueva de los Murciélagos in southern Iberia, uncovered during 19th-century mining activities, contained the best-preserved hunter-gatherer basketry in southern Europe, together with other unique organic artifacts associated with the first farming communities, such as sandals and a wooden hammer. We present 14 ^{14}C dates for the perishable artifacts (*N* = 76), situating the assemblage between the Early and Middle Holocene (c. 7500 to 4200 cal BCE). Our integrated analysis includes raw material determination and technological and chrono-cultural contextualization of this unique and important set of materials.

INTRODUCTION

Perishable organic raw materials are widely available and versatile, and have played a crucial role in human history. Wood, plant fibers, and skins have been used for the manufacture of multiple artifacts essential to the daily life of past populations. The poor preservation of such objects means that they can rarely be studied in detail, even though they are key to understanding human adaptations to environments and past technological and ecological knowledge, and provide insight into the diversity of needs for which these materials have provided a solution. For this reason, sites with well-preserved perishable materials present a unique opportunity to study past societies (*1*, *2*). Plant-based goods and tools were among the first artifacts in history, as suggested by the use-wear of lithic tools dated to early Pleistocene (*3*, *4*). The earliest direct evidence derives from the Middle Pleistocene (*5*–*8*), but examples are scarce and widely dispersed.

Most current knowledge of past societies is built from analysis of durable materials. Information relating to vegetal crafts in prehistory is limited (*1*) because of the lack of recovered remains, but, like nonperishable objects, plant-based artifacts allow us to study ethnicity (*9*–*11*), frontiers of culture and identity (*12*–*15*), trade networking (*16*, *17*), and human-environmental relationships including economy, adaptation, and subsistence (*18*–*21*). The craft of basketry is considered a particularly useful indicator for defining technological and cultural traditions (*2*).

The degree of preservation of perishable evidence depends on the contexts in which the materials are deposited or preserved. In southern Europe, good preservation in archaeological contexts dated to Mesolithic and Neolithic periods is extremely rare and restricted to a few sites where waterlogging, charring, or desiccation occurs. The sites of La Marmotta (c. 5840 to 5010 cal BCE) in west Italy (*22*) and La Draga (c. 5300 to 4700 cal BCE) in northeast Spain (*21*, *23*) are both lakeshore settlements of Early Neolithic date, and are well known for the exceptional preservation, due to waterlogging, of numerous organic items such as wooden artifacts, cordage, and basketry. In Iberia, plant-based materials from the Mesolithic-Neolithic are mostly preserved by charring and impression in fired clay, for example, at the Coves de Santa Maira (c. 11200 to 8200 cal BCE) in Alicante (*24*) and at Coves del Fem (4941 to 4545 cal BCE) in Tarragona (*25*, *26*). Material preserved by desiccation is concentrated in southeastern Iberia, which has a predominantly sub-arid climate. Most of such evidence has been recovered from Chalcolithic and Bronze Age sites, with Neolithic examples restricted to two textile fragments from Peñacalera Cave (c. 3462 to 3163 cal

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BCE) in Córdoba (*27*), and the outstanding examples of basketwork and wooden objects from Cueva de los Murciélagos in Granada (*28*, *29*) that are the focus of this article.

Cueva de los Murciélagos is one of the best-known sites in southern Europe for its exceptional preservation of organic materials by desiccation. The cave is a burial site identified in the 19th century by mining activities that uncovered partially mummified corpses accompanied by baskets, wooden tools, and other goods. Numerous critiques were published regarding the authenticity of the materials and their chronology (*30*, *31*). Questions persisted until the 1970s, when the first radiocarbon analysis was carried out on a sample of vegetal fiber and another from wood, both yielding Neolithic dates (5200 to 4850 cal BCE) (*32*). After the death of Manuel de Góngora (1884), the first investigator and owner of the remains, the archaeological materials became part of the first collections of the Museo Arqueológico Nacional of Madrid.

Here, we investigate the enduring transmission of Early-Middle Holocene plant-based technologies by analyzing the perishable artifacts of Cueva de los Murciélagos. We present a robust chronological assessment of the artifacts and other archaeological remains to contextualize our findings and provide a chrono-cultural sequence of the site. Our study also included the first geological characterization of the cave formation, explaining the preservation of the perishable materials. We analyzed the technological features and the raw material of plant-based artifacts, including a unique set of baskets, sandals, and wooden objects (table S1). Our research revealed that the plant-based artifacts of Cueva de los Murciélagos were produced in both the Mesolithic and Neolithic periods, providing evidence of the ways in which these technologies evolved through time. We also present the earliest and most diverse set of plant-based footwear documented in the prehistory of Europe.

Site background and archaeological record

Cueva de los Murciélagos [Albuñol, Granada, Spain; UTM (ETRS89) 483323.00-4073500.00] is a karstic cave, 7 km from the Mediterranean coastline of southern Spain and 2 km from the village of Albuñol (Fig. 1A). The cave was first accessed in 1831 by the owner of the surrounding lands who collected the abundant bat guano in the main chamber for fertilizer. The shelter was also used to keep goats until the identification of a vein of galena led to its exploitation by a mining company in 1857. The mining activities and the removal of blocks to access the mineral led to the discovery of a gallery that housed several partially mummified corpses accompanied by baskets, wooden tools, and other archaeological remains. The activity of the miners resulted in plant-based objects being burned and scattered around the outside of the cave, while other baskets and objects were distributed among the Albuñol villagers. Ten years after the discovery and subsequent looting, the cave was visited by the archaeologist Manuel de Góngora y Martínez who collected the testimonies of the miners regarding the artifacts, gathered the archaeological remains, and published accounts of them (*33*). He describes the remains of 68 individuals distributed in different areas. Most of these human remains have yet to be relocated. Góngora's publication associates the basketry and the wooden objects with the burials but without giving an exact location for each artifact. We know only that they were recovered from the floor surface in the inner part of the cave but have no information about the association of the objects or their original positions. The nonperishable materials from the site include ceramic sherds, blades and flakes of flint, quartz, polished axe head, bone awls, as well as diverse ornaments such as perforated shells, wild boar teeth, stone and shell bracelets (*34*, *35*), and a unique gold diadem. The pottery assemblage comprises globular vessels with impressed, incised, and almagra (red-painted) decorations (*36*). All the archaeological remains are now deposited in the Museo Arqueológico Nacional (Madrid), Museo Nacional de Antropología (Madrid), and Museo Arqueológico y Etnográfico (Granada).

Although the archaeological organic materials from Cueva de los Murciélagos have been cited countless times as the most well-preserved set of archaeological fiber-based materials in southern Europe, just three publications focus primarily on these materials (*28*, *29*, *37*). Alfaro (*28*, *29*) made the first systematic study of the fiber-based materials from the site regarding the technology of their production. Her publications reveal the main typologies of basketry, cordage, and sandals, with a catalog describing each object, adapting the terminology and technical variations. She specifies that the entire set of fiber-based objects was made from esparto grass (*Stipa tenacissima*) and explains the differences in the appearance of the raw material as due to the processing of the fiber through crushing the esparto—as is still traditionally done today. In a subsequent publication, Cacho *et al.* (*37*) detected geometric decorations on seven of the baskets using spectrophotometry analysis. Two sandals, a basket fragment, a piece of wood, and one undetermined object were dated by conventional radiocarbon methods, providing a chronology between 5200 and 4850 cal BCE (*37*), placing the site in the Early Neolithic of the region, and therefore representing an outstanding example of the earliest basketry in Europe. Although another wood sample provided an earlier chronology (6450 to 6030 cal BCE) (*37*), this was interpreted as due to the "old wood effect" and excluded from the interpretation. The possibility that this earlier date could be related to the use of the cave was previously postulated by some of the authors contributing to the present article (*38*). Our current study is the first to investigate these materials using an interdisciplinary approach combining geoarchaeology, radiocarbon dating and Bayesian modeling, raw material identification, and analysis of technological features.

RESULTS

Site geology and environmental conditions

Cueva de los Murciélagos is a karstic cave (Fig. 1 and the Supplementary Materials). The cave has a lenticular entrance, yielding direct access to the main chamber (Fig. 1C). The entrance is 15 m wide, oriented to the east; the cave is 60 m long and 30 m wide, with a drop of about 48 m between the highest and the deepest parts (fig. S1). It is located at the beginning of the lowest section of the Angosturas gorge, on its right bank, 450 m above sea level and about 70 m from the base of the gorge, on gray limestone that is highly fractured by Alpine tectonics (Fig. 1B). Impermeable rocks (chalcoschist and phyllite) are found very close to the base of the stratigraphic column, so the cave is subaerial with a few small globular speleothems (between 0.5 and 4 cm) (fig. S2). This limited development and growth of the speleothems is due to periods of low rainfall and/or high temperature, giving the cave practically zero humidity.

The set of plant-based tools

The perishable artifacts comprise 76 individual objects (table S1) including 10 wooden items (one of these being a composite

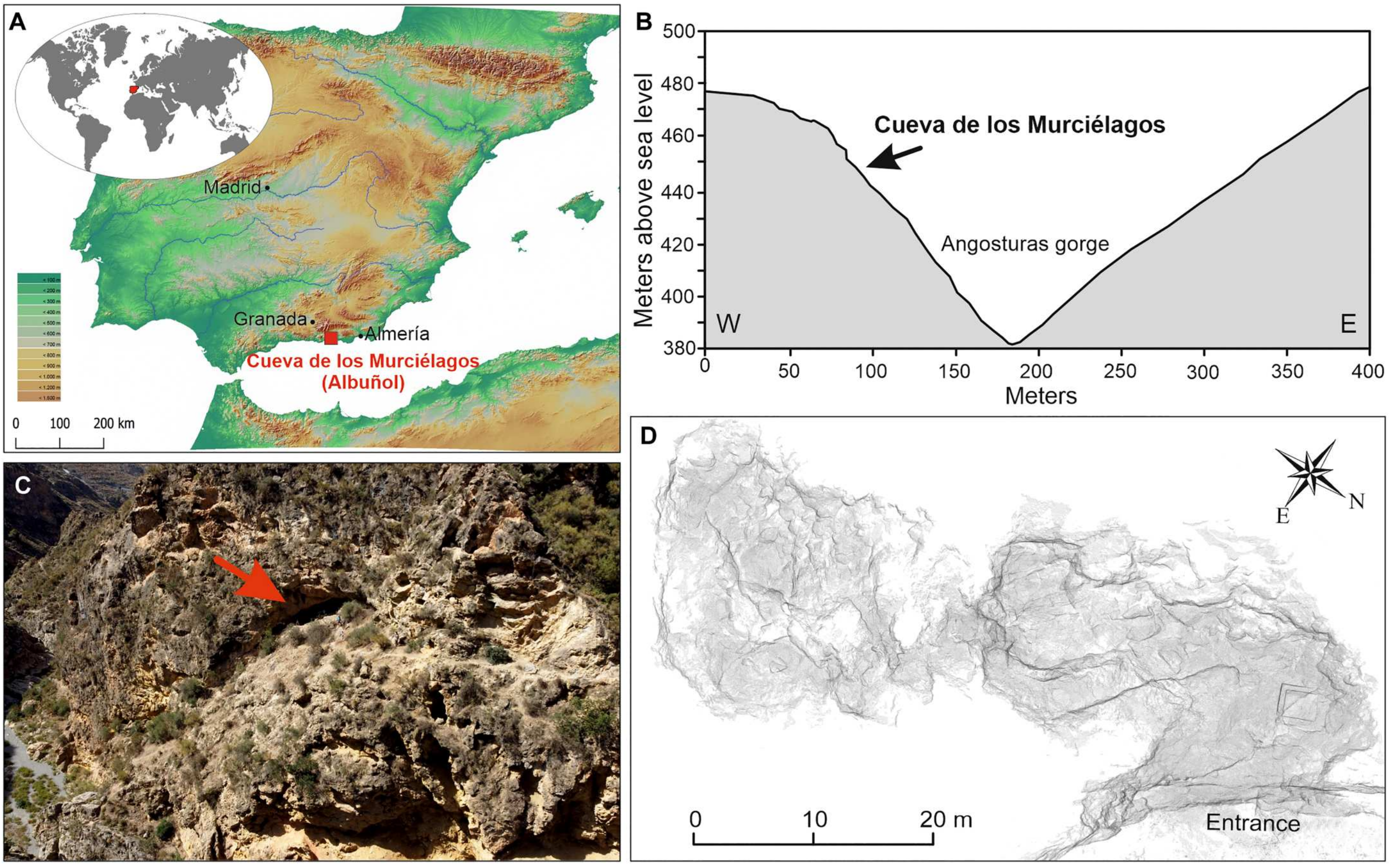

Fig. 1. The site of Cueva de los Murciélagos. (**A**) Location of Cueva de los Murciélagos in southeast Spain (Andalucía, Albuñol). (**B**) Elevation profile [east (E) to west (W)] of Angosturas gorge showing the situation of cave. (**C**) View from the north toward the Angosturas gorge and cave entrance. (**D**) Plan of the cave made with the 3D model.

object involving wood, reed, and vegetal fibers), 1 made of reed, and 65 fiber-based artifacts. Radiocarbon analyses were performed on a selection of 14 objects (Table 1); raw material and technological aspects were studied in detail for each of them. Analysis revealed that a variety of plants were used to provide wood, reeds, and fibers.

The wooden assemblage is heterogeneous, composed of worked wood, fragments of torches, and other wooden remains with no evidence of crafting (now under study). The present article focuses on the two wooden items that were dated by radiocarbon analysis: a pointed object (479) and a mallet (475). The pointed object (479) was fashioned from the branch of strawberry tree (*Arbutus unedo*) (Fig. 2, A to C), a shrub that produces a dense, hard wood. The mallet (475) was produced by longitudinally splitting an olive tree (*Olea europaea*) (Fig. 2, D to F) trunk, selected to have a lateral branch present at the required angle (Supplementary Materials).

Systematic analysis of the fibers used as raw material confirmed the use of esparto grass (*S. tenacissima*) for producing all types of baskets and cordage. Microscopic analysis showed microanatomical characteristics present on modern samples of esparto. These were absent on other Poaceae family, esparto-type plants (*Stipa gigantea* and *Lygeum spartum*) present near the site and used for comparison. Esparto leaves are naturally flat in shape, but in arid environments, they convolute to minimize their size and limit water transpiration (*39*). This convolution is visible in the transverse section of the leaves as protuberances on the abaxial face that contain the main isolated vascular bundles. Secondary vascular bundles are also visible all along the leaves, and these are surrounded by a thick layer of sclerenchyma tissue. The adaxial epidermis is glabrous, with alternated short cells known as rondels and long sinuate cells, and the absence of stomatal structures (Fig. 2G). The abaxial epidermis is characterized by a high concentration of silica hairs called tricomes (Fig. 2H). The parenchyma tissue is visible in Fig. 2I.

It was possible to distinguish differences in the processing of the fibers used in some objects with the naked eye, as previously indicated by Alfaro (*29*). While physical treatment, such as crushing, is easy to identify by observation or by histological analysis, other types of processing such as retting and fermentation are less visible. Our methodology was able to differentiate between raw, untreated esparto and crushed esparto that had been physically processed. Of the whole set of materials studied, 50.77% (33 of 65) of the objects indicate use of crushed esparto leaves, 41.54% (27 of 65) show raw esparto, and a further 7.69% (5 of 65) contain a combination.

The treatment of the fibers differs depending on the crafting techniques represented across the assemblage. For basketry, the esparto was either raw or crushed. Raw esparto was used for objects made from "twined" (both simple and diagonal) and "braided" basketry. Items fashioned using the "pseudobraided"/

Table 1. Results of radiocarbon dating from organic-based material from Cueva de Los Murciélagos.

Laboratory code	Object code	Object type	Material	Species	Sample weight (mg)	Analyzed (mg)	Method	Pretreatment	Date BP	$\delta^{13}C$ o/oo	Reference
Beta-628427	594	Pseudobraided/ cofín basket	Vegetal fibers	*S. tenacissima*	64.4	2.8	AMS-standard	Acid/alkali/acid: cellulose extraction: solvent extraction	6150 ± 30 BP	−21.0	This study
Beta-628426	626	Linked rings	Vegetal fibers	*S. tenacissima*	22.5	3.0	AMS-standard	Acid/alkali/acid: cellulose extraction: solvent extraction	8400 ± 30 BP	−21.4	This study
Beta-627342	617	Diagonal twined basket	Vegetal fibers	*S. tenacissima*	45.1	3.0	AMS-standard	Acid/alkali/acid	6210 ± 30 BP	−21.1	This study
Beta-627341	615	Coiled basket	Vegetal fibers	*S. tenacissima*	16.5	3.0	AMS-standard	Acid/alkali/acid	5580 ± 30 BP	−20.0	This study
Beta-627340	479	Pointed stick	Wood	*A. unedo*	1.8	0.59	AMS-micro-sample analysis	Acid/alkali/acid	6170 ± 30 BP	−22.4	This study
Beta-627338	475	Mallet	Wood	*O. europaea*	8.0	1.7	AMS-standard	Acid/alkali/acid	5660 ± 30 BP	−21.9	This study
Beta-627337	623	Pseudobraided/ cofín basket	Vegetal fibers	*S. tenacissima*	19.7	2.8	AMS-standard	Acid/alkali/acid	5570 ± 30 BP	−22.8	This study
Beta-627336	624	Pseudobraided/ cofín basket	Vegetal fibers	*S. tenacissima*	7.1	2.4	AMS-standard	Acid/alkali/acid	5550 ± 30 BP	−21.2	This study
Beta-627335	625	Braided basket	Vegetal fibers	*S. tenacissima*	18.5	3.4	AMS-standard	Acid/alkali/acid	5550 ± 30 BP	−20.3	This study
Beta-627334	581	Simple twined basket	Vegetal fibers	*S. tenacissima*	46.6	2.5	AMS-standard	Acid/alkali/acid	8300 ± 30 BP	−21.8	This study
Beta-627333	580	Simple twined basket	Vegetal fibers	*S. tenacissima*	73.0	3.3	AMS-standard	Acid/alkali/acid	8320 ± 30 BP	−19.6	This study
Beta-627332	579	Simple twined basket	Vegetal fibers	*S. tenacissima*	48.5	2.8	AMS-standard	Acid/alkali/acid	8350 ± 30 BP	−20.4	This study
Beta-627331	611	Simple twined basket	Vegetal fibers	*S. tenacissima*	14.4	2.7	AMS-standard	Acid/alkali/acid	5640 ± 30 BP	−23.7	This study
Beta-627330	603	Central core sandal	Vegetal fibers	*S. tenacissima*	66.3	3.2	AMS-standard	Acid/alkali/acid	5630 ± 30 BP	−23.5	This study
CSIC-1132	616	Coiled basket	Vegetal fibers	*S. tenacissima*					5861 ± 48 BP		(*37*)
CSIC-1134	609	Central core sandal	Vegetal fibers	*S. tenacissima*					5900 ± 38 BP		(*37*)
CSIC-1133	598	Central core sandal	Vegetal fibers	*S. tenacissima*					6086 ± 45 BP		(*37*)
CSIC-246	–	–	Vegetal fibers	–					5400 ± 80 BP		(*32*)
CSIC-247	–	–	Wood	–					7440 ± 100 BP		(*32*)

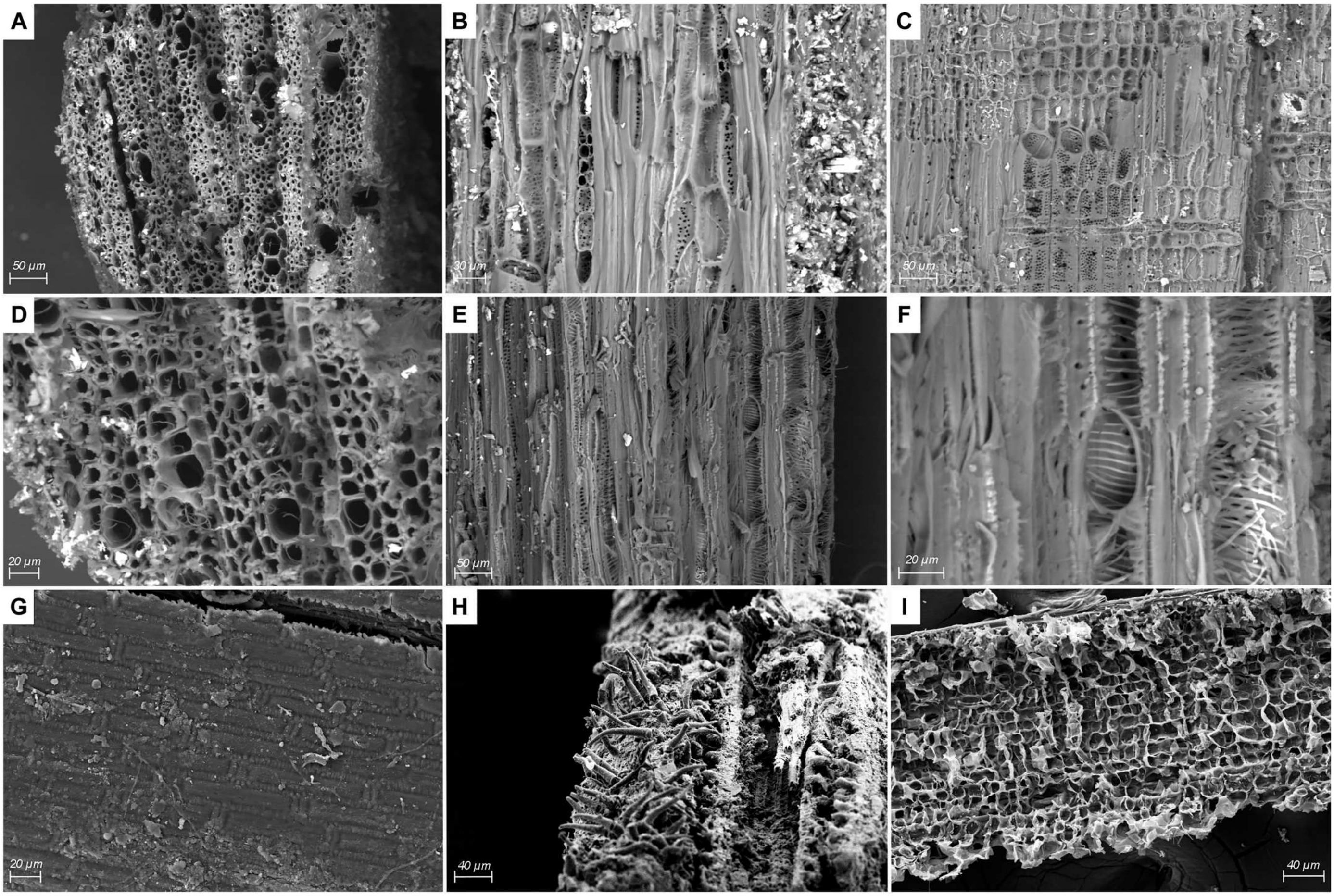

Fig. 2. Raw material scanning electron microscopy images. (**A** to **C**) 479 *A. unedo* wood (cross and radial sections). (**D** to **F**) 475 *O. europaea* wood (cross, tangential, and radial sections). (**G**) 582 *S. tenacissima* adaxial epidermal view. (**H** and **I**) 580 *S. tenacissima* abaxial epidermal view and parenchymatic tissue.

"cofín" technique were also produced primarily with raw esparto, except for a single object (619) made with crushed esparto. Raw esparto was also used for the bundles found in "coiled" basketry, while the stitches show opened fibers, indicating that the leaves had been crushed. For the cords, both twisted and braided, the fibers are crushed, and both types of sandals, "simple" and "central core," are also made with crushed esparto. Selection of leaves by size is also apparent. Analysis of the width of raw esparto leaves (it was not possible to measure crushed leaves) revealed that those used for coiled basketry (1.263 to 1.456 mm) and for a braided bag (1.513 mm) were wider than the leaves used in twined basketry (0.801 to 1.162 mm). For the pseudobraided/cofín technique, the width varied (0.745 to 1.258 mm).

Both of the wooden objects showed use-wear marks, ending their life cycle within the cave, discarded or intentionally deposited. The pointed object preserves the diameter of the branch from which the bark and the lateral branches were removed. Only the edge of the tool is shaped to obtain a point. Smashed fibers and polished surfaces on the pointed edge are identified as use-wear, but no fractures, notches, or erosions—indicative of use as a digging stick—are clearly visible to the naked eye. This object is therefore classified only as a "pointed stick." The head and handle of the mallet is roughly shaped, likely with cutting tools. Use-wear marks comprising smashed fibers and fractures are clearly visible on both head edges, and polished surfaces are present on the handle.

Two different basketry techniques are present: two-dimensional (2D), flat objects like mats, and 3D "baskets" (although baskets can be made with the same variety of techniques as mats). A standardized nomenclature of basketry production is still needed, although it has been discussed by many authors. Terminology is also affected by linguistic issues (*40*). Alfaro (*29*) identifies several basketry techniques in the Cueva de los Murciélagos assemblage: simple (N = 10) or diagonal twining (N = 7), coiling (N = 11), pseudobraided/cofín basketry (N = 6), and a particular type of basket constructed from knots on the base and called braided basketry (N = 1). Particular techniques are associated with the production of specific basket shapes and sizes. A detailed technological description of the dated objects is available in the Supplementary Materials.

Cords are also represented: a single piece (591b) of twisted cord with an S2z pattern, and a few three-strand braids (N = 5). Most of the cords seem to be part of other objects such as baskets, but mainly sandals, which have been fragmented by postdepositional processes.

Sandals form an important part of the inventory. Alfaro (*29*) distinguished two types: simple (N = 2) and central core (N = 20). Although no evidence of "laces" is conserved for the simple type, for the central core type, a small group of fibers emanating from the base of the sole may have been placed between the first and second toes. These fibers are also connected to a braid fixed to the middle of the sandal, which could be tied around the ankle. A single "ring" (626) and a nondetermined object comprising knotted fibers were not included in our analysis.

Chronology and Bayesian modeling of plant-based tools

The kernel density estimation (KDE) output from 19 radiocarbon dates (14 determined as part of the current research) indicates that the human deposition of plant-based artifacts in the site began around 7950 to 7360 cal BCE [95% highest probability density (HPD)] and ended in approximately 4370 to 3740 cal BCE (95% HPD) (table S2 and Fig. 3). The KDE model also reveals a first phase starting around 7960 to 7680 cal BCE (95% HPD) and ending around 7480 to 7150 cal BCE (95% HPD). After a hiatus, there is a second phase of intensity in around 5380 to 5070 cal BCE (95% HPD), lasting until 4390 to 4050 cal BCE (95% HPD). An intermediate peak is observed between these two phases that proceeds from the unidentified desiccated wood sample CSIC-247 [7440 ± 100 before present (BP)] (table S2 and fig. S3). This radiocarbon measurement is likely affected by inbuilt age issues and the wide-ranging standard deviation. We also carried out a model with KDE_plots of the radiocarbon dates of the two main phases. The estimates are analogous to those observed in the first KDE model (table S2 and Fig. 3A). Our results therefore suggest that the objects from Cueva de los Murciélagos were likely placed during two main chronological phases, separated by around 2000 years.

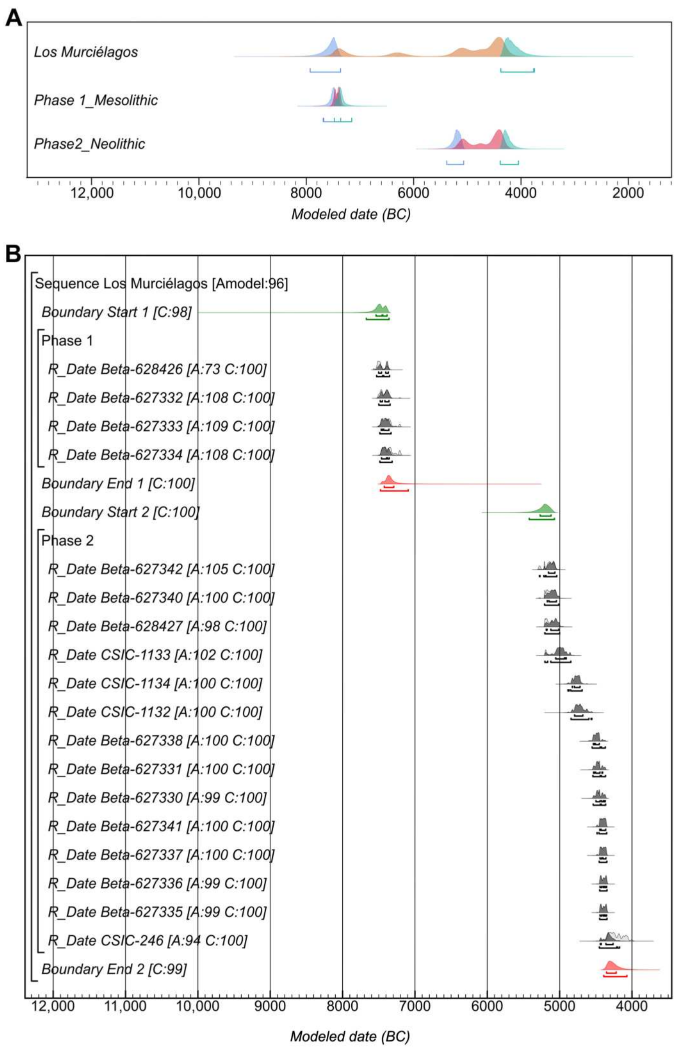

Fig. 3. Probability distribution of dates from Cueva de los Murciélagos. (**A**) KDE plots and Bayesian chronological ranges of the overall distribution of the dated events of Cueva de los Murciélagos and within each phase (phase 1, Mesolithic; phase 2, Neolithic). (**B**) Multiphase Bayesian chronological ranges for the estimated start and end of each phase and the modeled ranges of each radiocarbon date (except outlier). OxCal v4.4.4 Bronk Ramsey (*69*); r:5 Atmospheric data from Reimer *et al.* (*68*).

The Bayesian single model (*41*) included all the radiocarbon dates from the site, which yielded a good agreement (Amodel = 98.5; Aoverall = 98.4). The earliest evidence of human deposition of artifacts started in 7986 to 7391 cal BCE (95% HPD) and ended in 4373 to 3740 cal BCE (95% HPD) (fig. S3 and table S3). The modeled chronology indicates a period of human use of around 3110 to 4040 years (95% HPD) (table S3). These results are analogous to those obtained from KDE analyses. The results from the Outlier Charcoal model (see Materials and Methods) were also similar to those from the Bayesian single model (table S4 and fig. S4).

A Bayesian model of two sequential phases was created to consider the two main clusters of radiocarbon dates but excluding sample CSIC-247 (7440 ± 100 BP) (Fig. 3 and Table 2). The first phase comprises the four oldest radiocarbon dates, while the second phase contains the remaining measurements. The radiocarbon dates of phase 1 pass the test of contemporaneity {$T' = 6.3$ [T (5% = 7.8)]} (*42*), which means that the artifacts were probably deposited during a short period of time. The result of the model indicates a good agreement (Amodel = 96.6; Aoverall = 97.3) (Fig. 3 and Table 2). All the radiocarbon dates also show good agreement (A = >73%). Phase 1 starts in around 7680 to 7360 cal BCE (95% HPD) and ends around 7480 to 7100 (95% HPD). This phase was relatively short at 0 to 530 years (95% HPD) (Table 2).

The chronological gap between the end of phase 1 and the start of phase 2 was estimated at 2340 to 1780 years using OxCal's Difference command (95% HPD). Our results indicate a significant hiatus between phases 1 and 2 of around 2000 years (Table 2). Phase 2 begins in 5420 to 5070 cal BCE (95% HPD) and ends in 4390 to 4070 cal BCE (95% HPD). The analysis also indicates that the artifacts related to this phase were deposited in the cave over a long period {$T' = 897.189$ [(5% 22.4)]}, estimated at 740 to 1260 years (95% HPD). The results of the Charcoal Outlier model were also similar to those of the Bayesian two-phase model. We also tested a Bayesian model of three sequential phases including, as an additional phase, the desiccated sample CSIC-247 (7440 ± 100 BP), yielding high agreement indices (>95) in both the multiphase and outlier models (figs. S5 and S6 and tables S4 and S5). However, this model is not discussed here as the wide boundaries of this phase overlap the two main phases previously analyzed.

The attribution of the directly radiocarbon-dated objects to the identified phases on the site is as follows. The oldest artifacts, corresponding to phase 1 of the use of the cave, are 597 (Fig. 4A), 580 (Fig. 4B), 581 (Fig. 4C), and 626 (Fig. 4D) together with the piece of wood previously dated in the 1970s, the reference for which is unknown. The objects corresponding to phase 2 are 617

Table 2. Modeled dates and ranges for the estimated start, interval, and end for each phase of Cueva de Los Murciélagos. The estimated difference between phases 1 and 3 is also indicated.

Name	Unmodeled (BCE/AD)				Modeled (BCE/AD)				Indices Amodel 96.3 Aoverall 97				
	68.3%		95.4%		68.3%		95.4%						
	From	To	From	To	From	To	From	To	Acomb	A	L	P	C
Sequence Cueva de los Murciélagos													
Boundary start 1					−7540	−7387	−7673	−7359					98
Phase 1													
R_Date Beta-628426	−7531	−7384	−7576	−7357	−7504	−7370	−7531	−7353		73.3			99.8
R_Date Beta-627332	−7491	−7358	−7516	−7336	−7481	−7361	−7501	−7346		107.5			99.8
R_Date Beta-627333	−7469	−7343	−7507	−7196	−7469	−7361	−7487	−7332		109.2			99.8
R_Date Beta-627334	−7463	−7206	−7480	−7192	−7464	−7356	−7486	−7317		108			99.8
Interval 1					0	185	0	522					99.1
Boundary end 1					−7425	−7294	−7478	−7094					99.5
Boundary start 2					−5271	−5120	−5422	−5074					99.7
Phase 2													
R_Date Beta-627342	−5215	−5072	−5297	−5050	−5156	−5067	−5281	−5041		104.5			99.9
R_Date Beta-627340	−5208	−5054	−5214	−5015	−5173	−5046	−5210	−5013		100.1			99.9
R_Date Beta-628427	−5208	−5033	−5209	−5005	−5187	−5013	−5206	−5001		98.2			99.9
R_Date CSIC-1133	−5201	−4936	−5208	−4847	−5056	−4910	−5206	−4846		101.7			99.9
R_Date CSIC-1134	−4827	−4720	−4886	−4690	−4826	−4720	−4886	−4691		99.8			99.9
R_Date CSIC-1132	−4795	−4681	−4843	−4555	−4795	−4680	−4844	−4556		99.9			99.8
R_Date Beta-627338	−4536	−4453	−4581	−4369	−4535	−4453	−4552	−4370		99.8			99.9
R_Date Beta-627331	−4533	−4406	−4542	−4367	−4533	−4406	−4542	−4367		99.6			99.9
R_Date Beta-627330	−4498	−4371	−4537	−4365	−4499	−4371	−4537	−4366		99.2			99.9
R_Date Beta-627341	−4446	−4364	−4486	−4350	−4446	−4365	−4484	−4350		99.8			99.9
R_Date Beta-627337	−4443	−4360	−4454	−4348	−4443	−4361	−4454	−4348		99.8			99.9
R_Date Beta-627336	−4443	−4350	−4447	−4346	−4443	−4351	−4447	−4346		99.4			99.9
R_Date Beta-627335	−4443	−4350	−4447	−4346	−4443	−4351	−4447	−4346		99.3			99.9
R_Date CSIC-246	−4342	−4068	−4440	−3996	−4438	−4262	−4453	−4173		93.6			99.8
Interval 2					817	1046	744	1258					99.6
Boundary end 2					−4352	−4219	−4391	−4071					99.3

continued on next page

Name	Unmodeled (BCE/AD)	Modeled (BCE/AD)				Indices Amodel 96.3 Aoverall 97
Difference phase 1 to phase 2		−2257	−2034	−2340	−1783	99.4

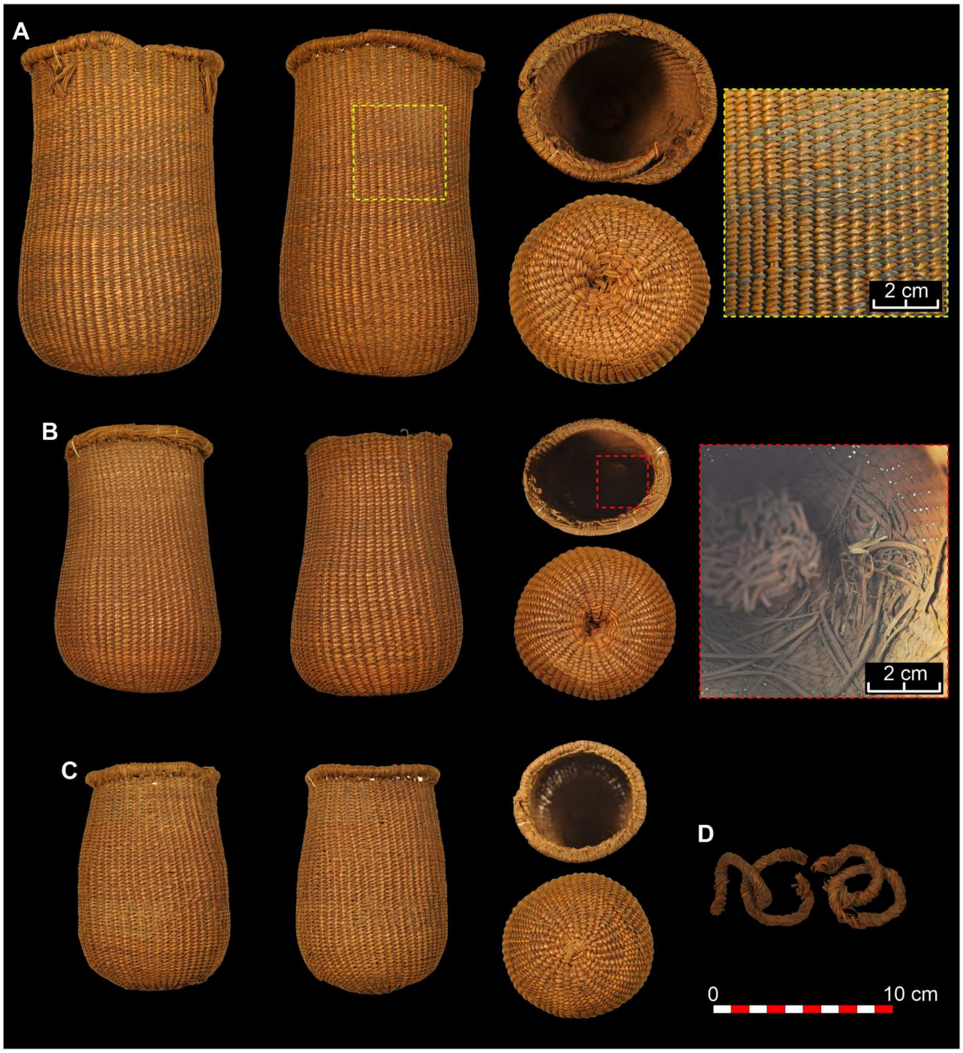

Fig. 4. Mesolithic organic-based artifacts. (**A**) Basket 579 (Beta-627332: 8350 ± 30 BP). (**B**) Basket 580 (Beta-627333: 8320 ± 30 BP). (**C**) Basket 581 (Beta-627334: 8300 ± 30 BP). (**D**) 626 Linked rings (Beta-628426: 8400 ± 30 BP).

(Fig. 5A), 594 (Fig. 5B), 479 (Fig. 5C), and, in chronological order, 475 (Fig. 6A), 611a (Fig. 6B), and 603 (Fig. 6C). The dates obtained in the 1990s correspond to 616a (Fig. 7A), 598 (Fig. 7B), and 609 (Fig. 7C). The last are 623 (Fig. 8A), 625 (Fig. 8B), 615a (Fig. 8C), and 624 (Fig. 8D). The most recent radiocarbon date obtained is that for a nonidentified object dated in the 1970s. A detailed description of each of the dated items is available in the Supplementary Materials.

DISCUSSION

The unique conditions for the preservation of organic material in the cave are related to the null humidity resulting from the geological character of the cave. Moreover, a dry wind current is generated by the prevailing climate in the area, and the north-south direction and narrow and deep morphology of the Angosturas gorge channel the wind toward the cave, through the narrow upper entrance. The wind cools as it travels through the cave, increasing in speed; it is cold as it exits through another narrow entrance located in the lower part of the shelter. The lack of prevailing humidity in the

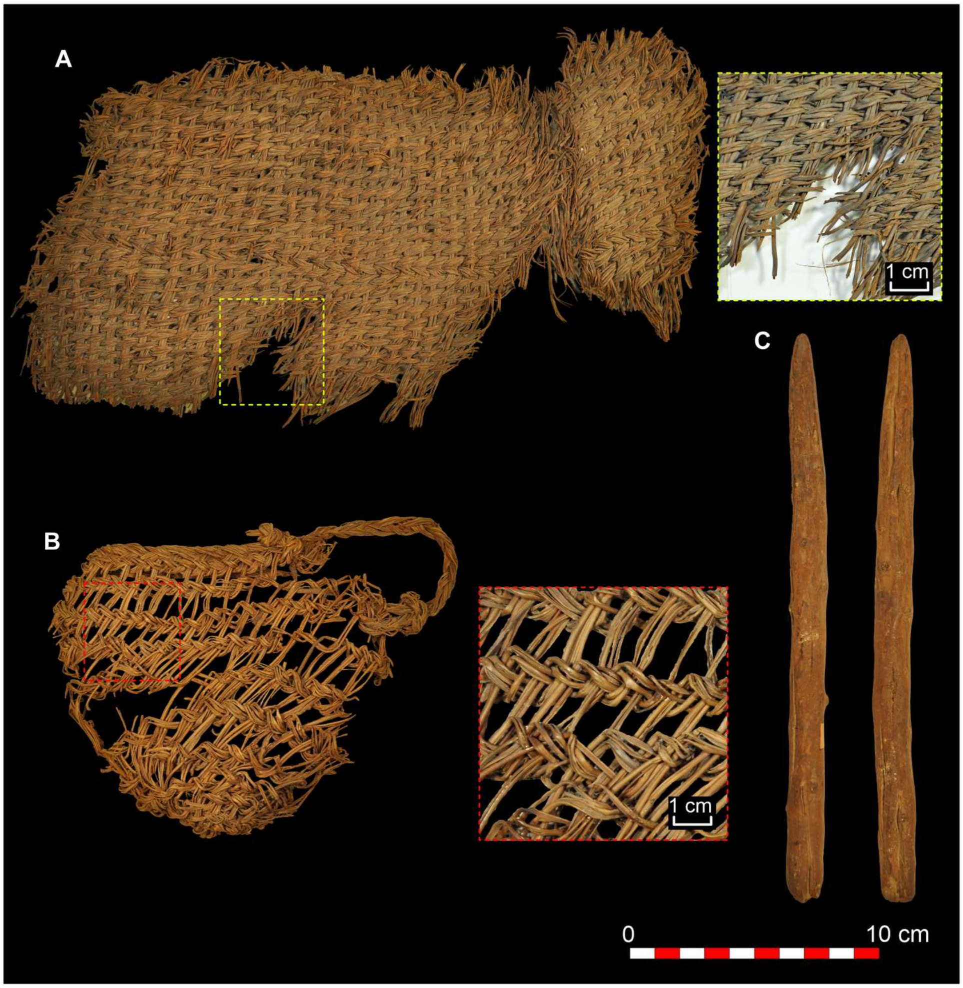

Fig. 5. Neolithic organic-based artifacts. (**A**) Basket fragment 617 (Beta-627342: 6210 ± 30 BP). (**B**) Basket 594 (Beta-628427: 6150 ± 30 BP). (**C**) Digging stick 479 (Beta-627340: 6170 ± 30 BP).

area and the circulation of wind in the cave as it cools and dries prevent the proliferation of bacteria, increasing the amount and diversity of preserved perishable material at the site. Unfortunately, the original contexts of the artifacts are unknown, so establishing associations is difficult. Even so, the characteristics of the fragments, in terms of the techniques used to make them, their measurements, and the raw materials and fiber processing used, suggest a refitting hypothesis for some of the pieces (table S1). According to Góngora (*33*), the materials suffered substantial fragmentation or charring when the lead workers burned them to keep their boiler working.

In summary, despite the mining activity, this assemblage represents one of the oldest and best-preserved collections of hunter-gatherer basketry in southern Europe. The sandals, baskets, and wooden artifacts with Neolithic chronologies constitute a unique sample of organic artifacts absent in other archaeological sites of early farmer communities. Previous studies assumed that all organic materials from the cave were Neolithic, based on three conventional radiocarbon dates (*37*). Our study, however, offers a fine-grained chronological framework based on accelerator mass spectrometry (AMS) radiocarbon dating and Bayesian modeling that clearly indicates two distinct main phases of deposition of plant-based objects, both occurring between the Early and Middle Holocene (c. 7500 to 4200 cal BCE), but each linked to periods having very different economic and social systems: The first phase of deposition is related to early Holocene hunter-gatherer populations, and the second phase is associated with Middle Holocene farmers. Other nonperishable materials from the site, like bone tools, lithics, and pottery sherds, confirm that the cave was used regularly by Early and Middle Neolithic populations, but beyond the organic-based objects, no other durable material can now be related to the Mesolithic use (phase 1) of the site. Our results also highlight that direct radiocarbon dates from plant-based objects are essential for understanding the depositional sequence of perishable materials in nonstratified archaeological contexts such as caves (*43*). This information also provides a chronological framework within which to integrate these objects, allowing more general archaeological discussions on the significance of plant-based technologies in human evolution. Furthermore, this contribution indicates differences between raw materials, techniques, and object typologies for each depositional phase in Cueva de los Murciélagos.

Fig. 6. Neolithic organic-based artifacts. (**A**) Mallet 475 (Beta-627338: 5660 ± 30 BP). (**B**) Sandal 603 (Beta-627330: 5630 ± 30 BP). (**C**) Sandal 611 (Beta-627331: 5640 ± 30 BP).

The Mesolithic fiber-based objects

The three dated objects (579, 580, and 581) corresponding to the earlier occupation phase of the cave (phase 1) are 3D twined baskets made with raw esparto. They are well preserved compared with the other fiber-based materials, being almost complete and decorated with geometric motifs made with dyed fibers (Fig. 2A); some incorporate human hairs or pigments (Fig. 2B). Other baskets recovered at the cave (582, 583, 585, 586, 586a, 586b, 592, and 593) share similar morphologies, techniques, and raw material, suggesting that they are also related to phase 1.

Simple twining is the only basketry technique clearly represented in the Mesolithic phase. It is not present in later periods and may thus be the oldest method represented in Cueva de los Murciélagos. The same technique has also been identified in basketry imprints on clay fragments from the Coves de Santa Maira site (Alacant, Spain, 12,900 to 10,200 cal BCE). Here, however, the imprints show space between the weft elements (open twining). In the dated baskets from Cueva de los Murciélagos, there is no space (closed twining), although there is one example of open twining that has not been dated (593). Our study therefore offers direct evidence of the oldest fiber-based objects made by hunter-gatherer populations in Iberia and in Europe. Elsewhere, fiber artifacts are associated with hunter-gatherer societies at various archaeological sites in the Great Basin (United States), where a notable number of objects made using a wide range of basketry techniques have been recorded, including plaited, twined, and coiled basketry (*13*, *14*, *44*).

Baskets 584 and 593 present variations of the twining technique, specifically regarding the warp, which gives a twill weave (584) and a diagonal twining (593) appearance to the baskets. The attribution of these examples to the Mesolithic phase is, however, unclear, but some of their characteristics, such as raw material measurements and preparation, are similar to those of the Mesolithic baskets. Only radiocarbon dating will confirm this hypothesis.

Four linked rings (626), whose function is unknown, also have hunter-gatherer chronologies. Góngora (*33*) suggested that the rings were part of an ornamental necklace, although no further information is available. Five rings were preserved in the 19th century, but only four now survive. No other objects or techniques are

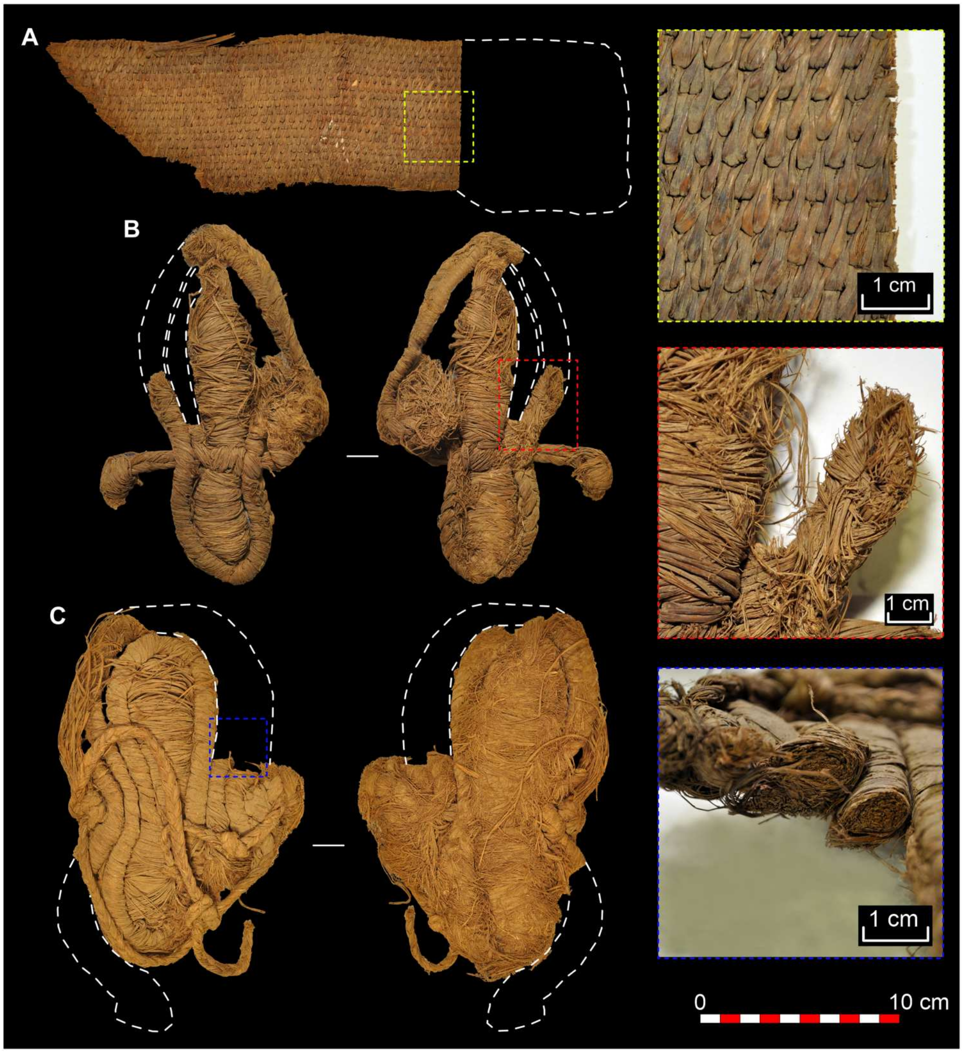

Fig. 7. Neolithic organic-based artifacts dated in previous work with detail of damage. The white dashed line shows the portion of the object now lost. (**A**) Basket fragment 616a (CSIC-1132: 5861 ± 48 BP). (**B**) Sandal 598 (CSIC-1133: 6086 ± 45 BP). (**C**) Sandal 609 (CSIC-1134: 5900 ± 38 BP) (*32*, *37*).

represented in phase 1. Only raw esparto was used for the twined Mesolithic baskets and the linked rings. No evidence of physical processing of the fibers was identified in the earlier chronologies of the cave. Although the twining technique and its variations can be achieved with crushed esparto, processing was not used during this phase.

The Neolithic perishable objects

Phase 2 of Cueva de los Murciélagos encompasses a wider diversity of objects, techniques, and raw material processing. The plant-based artifacts include cords, 2D and 3D baskets, and sandals made with several techniques. The modeled dates of three pieces (594, 623, and 624) place the pseudobraided or cofín technique in this phase. These items were selected for radiocarbon analysis because of differences in their morphology and the treatment of raw material, but this technique is also present in three other objects (618, 619, and 621). Object 594 is an almost complete bag. It shows space between the pseudobraids, as is also observed in the second object, 623, a formless fragment. Fragment 623 is the only cofín object, which is made of crushed esparto. The third item, 624, is a 2D object that exhibits both closed and open pseudobraiding in different areas. Object 617 is the only example of diagonal twining documented in this phase. Other undated objects (622, 627, 627a, and 627b) present similar techniques and raw material, which suggest that they may also be attributed to this phase. These are all fragmented, and no specific object shape can be identified. The esparto used in these pieces is raw, as used for the simple twining baskets in phase 1. This group of plant-based objects provides the only evidence of diagonal twining, pseudobraided/cofín, and braided baskets in the prehistory of the Iberian Peninsula and, indeed, that of Europe. No earlier parallels are documented, indicating that these techniques may originate exclusively from south Iberia.

The unique braided basket or bag (625) also corresponds to the Neolithic phase. In this object, the esparto leaves are, again, used in their raw state. The coiled basketry technique is represented in this phase by two artifacts: one (616a) dated in the 20th century (*37*), and one (615) dated within the present study. With regard to the processing of the esparto, it is important to differentiate between

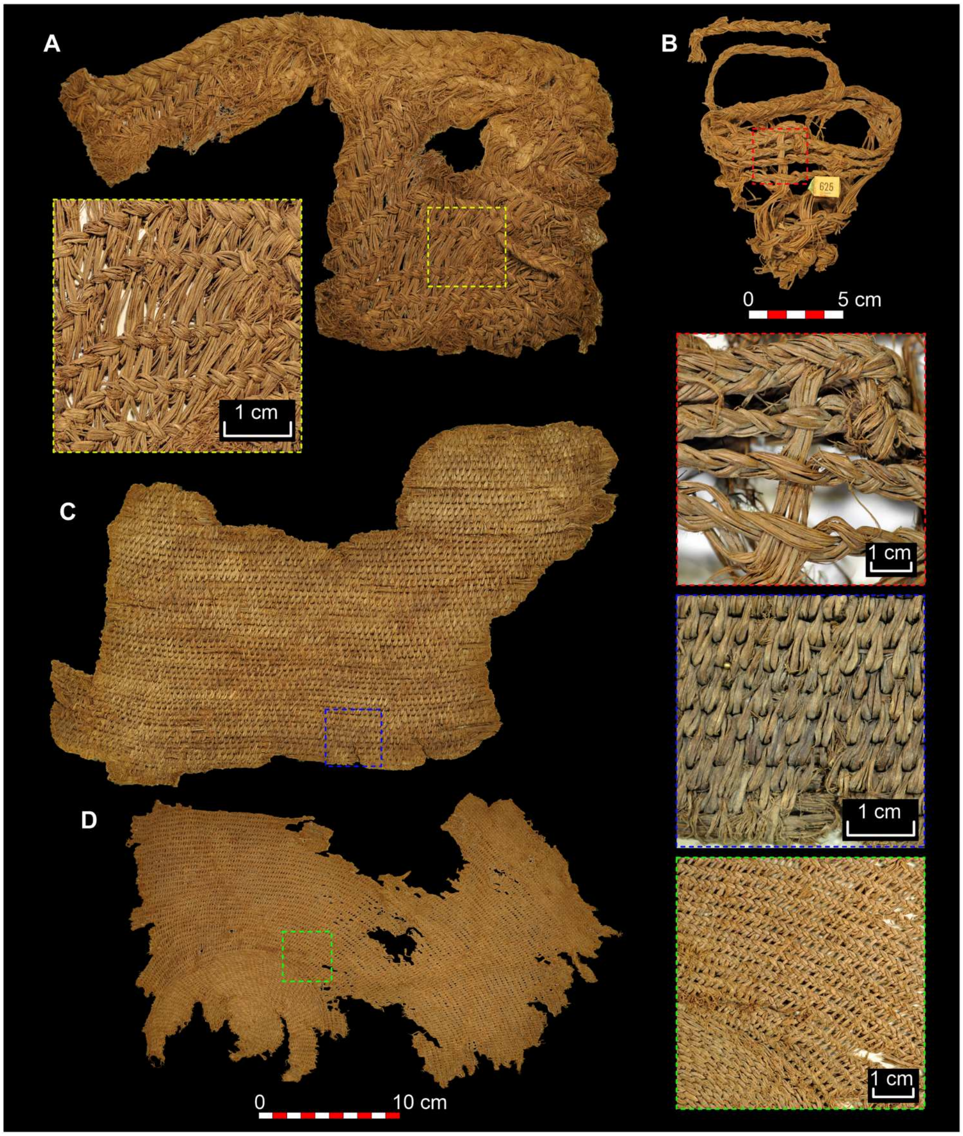

Fig. 8. Neolithic organic-based artifacts. (**A**) Basket/mat fragment 623 (Beta-627337: 5570 ± 30 BP). (**B**) Basket 625 (Beta-627335: 5550 ± 30 BP). (**C**) Basket fragment 615 (Beta-627341: 5580 ± 30 BP). (**D**) Basket/mat fragment 624 (Beta-627336: 5550 ± 30 BP).

the active and passive elements of the coiled baskets. The stitches (active) are always made using crushed esparto (except for object 620), while bundles (passive) can comprise either raw or crushed esparto, although the degree of crushing differs across the objects. This technique is represented in nine further pieces (587, 588, 589, 590, 616b, 620, 627c, 627d, and 627e). Contemporaneous examples have been documented in western Mediterranean sites, including La Marmotta (Lazio, Roma, c. 5840 to 5010 BCE) (*22*), La Draga (Girona, 5207 to 4862 cal BCE), and Coves del Fem (Tarragona; 6065 to 4545 cal BCE) (*25*, *26*). In La Draga, eight coiled baskets were identified, made of fibers from various monocot families (Poaceae, Cyperaceae, and Typhaceae) and lime tree (*Tili*a sp.). A coiled basket made of Cyperaceae fibers, found covering a pit and related to storage purposes, was found at Coves del Fem (Tarragona; 6065 to 4545 cal BCE) (*25*, *26*). The coiling technique therefore seems to be the most widely used in southern Europe during the Neolithic.

Twenty-two artifacts corresponding to two typologies of fiber-based sandals were found in the cave. Our radiocarbon analysis of a simple sandal (611) and a central core sandal (603) agrees with the previous analysis of two central core shoes (598 and 609) (*37*), confirming that they date to the Neolithic period. No chronological differences are visible between the two forms, although the central core type is most common. Other examples of shoes have been recovered in Europe, including one from a pit in the Areni-1 Cave (Armenia, 3627 to 3377 cal BCE). This was made of leather and a large number of grasses (*45*). Sandals made with lime bast (*Tilia* sp.) and ramie (*Boehmeria nivea*) were recovered at the Allensbach site (Germany, c. 3000 cal BCE), being very similar to examples found in Sipplingen (Germany; 2900 cal BCE) (*46*). The footwear associated with the Ötzi (Italy, 3350 cal BCE) present a sock-like structure made of lime/linden bast and covered with leather (*47*, *48*), and similar to a shoe found at the Sutz-Rütte site (Switzerland; 2750 cal BCE (*49*).

The various sandals mentioned above are completely different in technological terms from those found at Cueva de los Murciélagos in that, although they used grasses in their structure, other materials including leather, lime, and ramie bast were also used. Further studies should be undertaken regarding this aspect of the fiber-based collection, which potentially contains both direct and indirect information about the population that wore the sandals. This would be of interest given the loss of the human remains extracted from the cave in the 19th century. The esparto used in sandals is always crushed, and this may be directly related to their function as they needed to be flexible and comfortable to wear. This sandal set therefore represents the earliest and widest-ranging assemblage of prehistoric footwear, both in the Iberian Peninsula and in Europe, unparalleled at other latitudes.

Cord elements are also recorded in the cave, and these are either twisted or braided. Most seem to be detached fragments from basket handles or cords used to tie sandals to the feet. The Neolithic site of La Draga has yielded examples with an extended S and Z twist, and braided cords made of lime tree and nettle (*Urtica* sp.) (*21*), and a small twisted strand made of an undetermined monocot family was also recovered from Coves del Fem (*26*). One twisted cord example from Cueva de los Murciélagos (591b) is especially striking. The vegetal material used to produce this cord is heavily crushed. No specific association can be made with braids, although these are also made with crushed esparto. The twist (S2z), measurements, and processing of the fibers are similar to those of the bowstring associated with Ötzi (*50*) and with a possible bowstring roll from La Draga (*21*). The similarity of the twisted cord to these examples suggests that it could also be a bowstring; several arrow shafts recovered from the same context in the cave confirm that archery was practiced.

Technological features

The esparto grass shows evidence of several processing methods, which produce distinctive working characteristics and which influence the typology and the aesthetics of the final object. Esparto artisans traditionally collect the leaves in the summer months. They are then dried for 20 to 30 days (*51*, *52*) to produce "raw" esparto or en rama, which can be used for crafting after rehydrating by water submersion for approximately 24 hours. The nomenclature en rama refers to the fact that the leaves are complete and have not suffered physical damage. The dried, raw esparto can be further processed for specific applications by retting in stagnant water for 20 to 40 days to produce an anaerobic fermentation resulting in the decay of organic materials such as lignin. The organic degradation is halted by drying the material. The timing of this process is dependent on environmental conditions such as temperature and humidity. There are no standardized parameters because it is a traditional process that varies depending on the artisan and their experience. The material resulting from this processing is known as "cooked" or "retted" esparto and is traditionally acknowledged to be more resistant and flexible than raw esparto. The retted esparto can be rehydrated in the same way as the raw esparto (to produce cooked en rama esparto) or can be crushed physically using a wooden mallet to break the leaves and extract the fibers, creating "crushed" esparto. In later periods—and linked to industrial processes—the thinnest fibers are extracted by combing with a comb to produce "combed" esparto.

Given the possible variations in esparto processing, although the appearance of the leaves in phase 1 (Mesolithic) indicates that they are not crushed, this does not mean that they did not undergo preparation. Although no microscopic differences are detectable to indicate whether the esparto is retted/cooked, rehydration of the fibers would be needed to make them malleable and useful for crafting. None of the objects in the cave could have been produced using dried fibers, so raw material would have been prepared by hydration before the items were fashioned. Further, the esparto leaves used in the Mesolithic objects present a smaller diameter (0.801 to 1.162 mm) than those used in the Neolithic phase (1.263 to 1.513 mm), except for the material used in some specific pseudobraided artifacts. This could indicate the selection of younger esparto leaves for Mesolithic crafting. It is important to highlight that the physical treatment of crushing the leaves is evidenced only in Neolithic materials, suggesting that this practice was not used in earlier periods. A degree of humidity is still needed when using crushed esparto, but to a lesser extent. Histological differences in the cross section of the leaves are visible in some of the samples. These may be related to the part of the leaf where the sample originated (apical-basal)—which is difficult to determine during sampling from archaeological objects—or to its growth stage. Our results therefore indicate an extended knowledge of the plant resources within the local environment and a high level of understanding and expertise among the last hunter-gatherer populations and, most likely, their continuity toward the first farming societies.

The wooden remains studied are also unusual within the archaeological record in southern Europe. The raw material, size, and morphology of the pointed object (479) are similar to those of Neolithic digging sticks, such as the set from La Draga (*53*); however, some technical features are absent, including the fire treatment of the point. In the case of the wooden mallet (475), a parallel with the same morphology but different size has been identified in a Neolithic context at Meare Heath (Somerset, UK) (*54*). The same approach, using wood from the trunk and a branch as a handle, has been identified at several other Neolithic sites, where it has been used for crafting adze or axe handles and spoons (*55*, *56*). It has been suggested that the mallet could have been involved in the processing of vegetal fibers. It is notable that this artifact is contemporaneous with the evidence for the use of crushed esparto for crafting purposes in the Neolithic phase of Cueva de los Murciélagos.

Typologies and function of the plant-based artifacts

This assemblage presents an unprecedented diversity of basket typologies and techniques compared to other Mesolithic and Neolithic sites in the Mediterranean region. This high variability may be related to the unusual environmental conditions of the cave and its impact on the conservation of the plant-based artifacts. Other Mediterranean Early Neolithic sites preserve these artifacts under waterlogged conditions, as at La Marmotta (*22*) and La Draga (*57*), or by carbonization as at the Coves del Fem (*26*). The desiccating conditions of Cueva de los Murciélagos likely favored greater preservation of organic materials, yielding a wider variability of preserved artifacts. The nature of the human activities in the cave during both Mesolithic and Neolithic periods may also explain this distinctive assemblage. In contrast to the preserved organic objects from La Marmotta, La Draga, and Coves del Fem, which were recovered from domestic contexts (so basket fragments probably correspond to discarded elements), we know from 19th-century accounts that the objects found in Cueva de los Murciélagos were associated with burials (*33*). Unfortunately, only a few of these human remains have been preserved in the museum and they have not yet been dated. We cannot, therefore, determine whether all the plant-based objects were related to burial practices as there is no contextual information for the finds; they may have been the result of single or multiple events of deposition over time.

The most prevalent functional category of the plant-based objects is the "container." Our results highlight the diversity of items in this category in terms of shape, size, raw material, and preservation. They include objects made of carved wood and 3D basketry, both rigid and flexible. Bayesian modeling of the radiocarbon dates indicates that the oldest basket elements are the semi-rigid, simple-twined baskets, with a very closed weft, and others with similar shapes but different sizes. Some contain rare materials such as hair and mineral pigment, and this, together with their extraordinary state of preservation—mainly complete—suggests that they were introduced to the cave for a unique purpose, which is consistent with their use in funerary practices during the Mesolithic (phase 1).

Our results suggest differences in the functions of Mesolithic and Neolithic plant-based objects. The Neolithic containers are more diverse than those from the Mesolithic in terms of shape, size, raw material preparation, and state of preservation. The Neolithic basketry objects are largely fragmented, preventing their identification as either 2D or 3D artifacts. The flexibility and diversity in shape and size also suggest a greater range of functions compared with the Mesolithic basketry. Flexibility is a valuable attribute for transport, and the more open or closed the weft and warp, and the presence of active and passive elements (depending on the technique) can be related to the type of material to be contained (*2*). 2D basketry often corresponds to mats. The description of the finds provided by Góngora (*33*) indicates that the individuals buried in this cave wore textiles made of esparto grass, as well as hats and sandals. The only remains in both museum collections that can be identified as clothing are the sandals, all the dated examples having Neolithic chronologies. Some sandals had clear use marks, while others were apparently never used, suggesting that while some individuals were buried with their daily clothing, others had specific clothing prepared.

In summary, the technology and finishing of these baskets and tools from Cueva de los Murciélagos open up groundbreaking perspectives on the complexity of Early-Middle Holocene populations in Europe. They provide insights into the perishable material technologies used on plants and into the knowledge involved in the acquisition and processing of these plants. Only a small sample of basketry from the cave has been dated, and although these objects are representative of the typology of organic objects recovered, not all the organic remains can be ascribed to these periods. Further radiocarbon analyses are needed to corroborate these initial hypotheses.

Plant material culture offers unique insights into the life of prehistoric societies. Lack of preservation has meant that perishable materials have not previously been extensively considered during archaeological research. It is vital that, where they do survive, these materials are the focus of detailed study to further examine the role of such technologies during prehistory.

MATERIALS AND METHODS

Cave geomorphology and 3D documentation

To study the geomorphology of the cave, in situ data on the various speleothems present were recorded. The morphological characteristics and the dimensions of these formations, which are created by chemical precipitation (dripstone, existence or not of flowstone, complex shapes, etc.), were described. A complete topographical model of the entire cave was constructed using two different laser scanners: a portable NavVis VLX manual and a fixed portable FARO Laser Scanner Focus3D. A virtual 3D visit to the cave is available at: Cueva_Murciélagos - FARO WebShare (websharecloud.com).

Raw material identification and technological analysis

An inventory of the whole set of perishable objects was produced, many of which were also included in previous studies (*28*, *29*). The objects were described during observation in the museum, and the documentation was enhanced with an extensive photographic record, created using a Nikon D5000 camera with a NIKKOR AF-S DX 18-55 mm VR lens. More detailed images were captured using a portable digital microscope (Dino-Lite Edge Digital Microscope AM7915MZT) with a magnification of ×20 to ×220. The volume of the baskets studied in this work has been calculated with the free software Blender 3.5.1 using the revolution 3D model of the baskets.

Wooden objects were taxonomically identified following standard methods by observing the three anatomical sections of wood: cross, tangential, and radial (*58*). Each object was observed under the portable digital microscope. Where possible, a tiny wood sample was obtained from cracks or broken areas for further analysis. These samples were observed under a scanning electron microscope (ZEISS EVO LS 15, RIAIDT-USC). Diagnostic features were compared with atlases of wood anatomy (*59*–*63*).

In tandem with taxonomic identification, dendrological features from the wooden objects, such as plant part (trunk, twig, root) and tree-ring curvature, were also registered using qualitative categories (strong, moderate, weak) (*64*). Other features related to taphonomic aspects were also documented, such as evidence of biodeterioration (xylophagous galleries, fungal hyphae) (*65*, *66*). In addition to aspects related directly to their raw material, objects were described in morphological terms, and technical aspects of their crafting were recorded, along with other features related to their life cycle (use, repair, reuse) (*67*). Last, they were classified according to their function or their morphology when function was unclear.

Fiber-based objects were sampled using tweezers and a blade cleaned with ethanol 96% between each different object to avoid cross-contamination for further studies. Although sampling is a destructive process, very small fragments are needed for identification analysis. Because of the fragility of these objects, small parts break off during restoration and storage processes and, in most cases, it was these fragments that were sampled to avoid further damage to the objects. In just one case, 592, sampling was not possible because the object was completely consolidated, and sampling could have been damaging. Identifications were performed under ×50 to ×500 magnification using a transmitted light bright-dark field Olympus BX51 microscope coupled with an Olympus DP26 camera and linked to Olympus cellSens software. Some samples were placed on stubs using double-sided carbon tape and were coated with a 15-nm layer of gold using the Emitech K550 Sputter Coater Unit to be observed under a Zeiss Merlin field-emission scanning electron microscope. Fiber taxonomic identification was based on the anatomical and histological description of the archaeological samples and by comparison with modern species collected in the immediate area of the site. Alfaro (*29*) identified the raw material as "esparto grass" but provided no other details. Because of the variety of Gramineae known as esparto, the archaeological samples were compared with a reference collection of similar plants also used in fiber crafting activities, and which also grow naturally close to the site. These included species of different genera such as *Stipa* (*S. tenacissima*, *S. gigantea)* and *Lygeum* (*L. spartum*).

Other characteristics of the raw material were also recorded, including the size of the leaves and their integrity, to identify the criteria used to select the fibers. The diameter of the leaves was measured to check for differences in the raw material selection in relation to the technique used and processing method applied, and to the chronology of the materials.

A standardized nomenclature for basketry production is still needed. Terminology has been much discussed and used differently by many authors throughout history; it is also affected by linguistic issues (*40*). The vocabulary used by Adovasio (*2*) is applied here to describe the functional relationship between passive (warp) and active (weft) elements of fiber-based materials, but some techniques are not covered, so the work of other authors was also considered (*28*, *52*). The basketry techniques were therefore classified as simple or diagonal twining, coiling (*2*), cofín (*52*), or pseudobraided (*29*), and a specific type of basket with knots on the base called braided by Alfaro (*29*). Descriptions of the techniques are presented below using this nomenclature. Each object exhibited individual characteristics not detailed here. Detailed accounts of the dated objects can be found in the Supplementary Materials.

In our study, we refer to weft twining that consists of vertical, passive warps linked by an active weft, which forms a twisted cord around them. In closed twining, no space is visible between the weft strands. The newly added fibers of the weft are visible on the inner surface. Simple twining presents a single warp around the whole basket, while in diagonal twining [also called rhomboidal twining by Alfaro (*29*)], a pair of warps alternates in each round of the basket production, creating a diagonal pattern on the finished object. The coiling technique involves a passive, wrapped bundle or foundation wrapped by active stitches or a winder, forming a spiral. There are variations in the typology of the sewing element. The cofín (*52*) or pseudobraided (*29*) basketry technique involves braiding three bundles of fibers, one of which is changed in each round, forming the warp of the basket. The technique may be "closed" or "open," depending on the distance between the braided rows. This method has been documented only in Iberia (various chronologies) and does not appear in basketry atlases. The final basketry technique documented in the Cueva de los Murciélagos is braided (*28*). This rare type is not described in basketry handbooks. Five knotted fiber bundles on the base of the basket form the warp. They pass several times toward a braid (weft) started from one of these five knotted bundles, which increases in the number of braids and makes the basket larger at the top. It is finished with a wider braid, wrapping the leaves from the warp and the weft, and has a braided handle.

Cords are also represented within the materials from Cueva de los Murciélagos. Braids are most common form, with only a single example of the twisted form, this having an S2z pattern. Most of the cords seem to be components of other objects such as baskets and sandals, which have been fragmented by postdepositional processes.

Sandals represent an important part on the inventory of the fiber-based materials from the cave. Alfaro (*28*, *29*) distinguished two types: simple and central core. Simple sandals consist of a braid wrapped around itself, which shapes the sandal sole and makes it wider. Central core sandals are based on a bunch of wrapped fibers that forms a central core, which is surrounded by fiber bundles, increasing the width of the sole. The front of the sole is always wider than the back because it includes one extra bundle. Although no evidence of tying elements was conserved for the simple sandals, in the central core type, a small group of fibers originating from the bottom of the sole may have been placed between the first and second toes. This element is connected to a braid in the middle of the sandal, which could have been fixed to the instep and tied around the ankle. Other objects (e.g., 626) are not described here because they are singular elements, the typologies of which have not been determined.

Artifact selection and sampling

Selection of objects for radiocarbon dating was based on criteria including sample availability, raw material, technology, and typology. A set of 14 artifacts representing the complete typology of the assemblage was selected for dating. Of the wooden artifacts, the hammer (475) and the digging stick (479) were chosen because of their unique presence in the set but were also prioritized as they were partially broken with areas available for sampling. Obtaining samples from other wooden materials was not possible because of preservation issues (472, 473, 474, 1140, 1141, 1165, 1138/532, and 1139/532). For the vegetal fiber–based materials, the dating selection covered the basketry techniques of twining (579, 580, 581, and 617), coiling (615), cofin basketry (594, 623, and 624), the special basketry technique with knots on the base (625), and the four linked rings (626). Last, the two types of sandals were chosen: the simple circular string (611) and the central core type (603). Only one piece (592) in the fiber-based set could not be sampled because of complete consolidation.

Radiocarbon dating

Our analysis considered 18 radiocarbon dates: 14 made in the framework of this research and 4 from published results (*32*, *38*). Radiocarbon dates for the present study were obtained from Beta Analytic Laboratory (Miami, USA). Sampling was carefully undertaken to preserve the total integrity of the objects, taking small fibers or fragments from areas of breakage. The weight of each sample was around 0.5 mg (Table 2). At the level of taxon, the material was found to belong to short-lived terrestrial species: 12 were plant material (*S. tenacissima*), and 2 samples were wood (*A. unedo* and *O. europaea*). Thirteen samples were dated by AMS standard, and one was dated by AMS-Microsample (Beta-627340) due to the small size of the wood sample. The samples were pretreated with acid/alkali/acid: The sample was gently crushed and then dispersed in deionized water; it was then washed with hot HCl acid to eliminate carbonates and then treated with an alkali wash (NaOH) to remove secondary organic acids. This was followed by a final acid rinse to neutralize the solution before drying. For two of the samples (Beta-628427 and Beta-628426), it was necessary to carry out a complementary cellulose extraction pretreatment to remove solvents resulting from restoration. This followed the full acid/alkali/acid pretreatment and involved bathing the samples in sodium chlorite ($NaClO_2$) under controlled conditions (pH 3 and temperature at 70°C) to eliminate all components except wood cellulose.

Our analysis also considered five radiocarbon measurements obtained using standard radiometric dating at Consejo Superior de Investigaciones Científicas (Madrid, Spain) (*37*). Four samples correspond to short-lived terrestrial species, and one to an unidentified desiccated wood artifact (Table 2). All the radiocarbon measurements were calibrated with the internationally agreed IntCal20 atmospheric calibration curve (*68*).

Bayesian chronology

The radiocarbon measurements were subjected to Bayesian analyses to obtain reliable estimations of the start, end, and duration of deposition of the artifacts in Cueva de los Murciélagos. Our analyses were performed using the OxCal online software version 4.4 (*69*). The two-sigma probability interval (95.4%) was used when discussing the ^{14}C measurements, and the one-sigma probability interval (68.2%) was added in the tables and figures, as recommended by Millard (*70*). The degree of contemporaneity between the different radiocarbon measurements was tested through the chi-square test (*42*), which assesses the degree of overlap between the probability ranges of each of the dates.

We first applied nonparametric statistical methods based on KDE (*71*) as an exploratory mode to characterize the potential phases of the human deposition activities in the cave through time. KDE methods allow the identification of discontinuities in the probability distribution that may relate to several chronological phases (*71*). These methods are widely implemented when there is no formal prior data, reducing the noise from the calibration procedure (*71*). We used this method as the analyzed samples originate from historical excavations, and there is a lack of information regarding the stratigraphic relationships between them (*71*). We used the KDE_Plot Oxcal tool (*71*, *72*).

The uncalibrated radiocarbon dates were also modeled using single uniform phase and multiphase models (*72*). This approach combines the radiocarbon dates in a uniform distribution model based on the hypothesis that all the dated events have the same likelihood of occurring at any time at the start and end of the phase. The model then calibrates the radiocarbon dates based on prior information from other early measurements of the chronological phase. The model was developed using OxCal tools (Sequence, Phase, Boundary, Interval, and Difference commands).

We also modeled the radiocarbon dates with the Charcoal Outlier model (*41*, *73*). This model is designed to lessen the impact of potential inbuilt age issues, as three measurements correspond to undetermined and long-lived desiccated wood samples (Table 2). The Charcoal Outlier method provides younger age estimates, as the correct age of the modeled events is more recent than the nonmodeled calibrated radiocarbon dates (*73*). A prior 5% probability of being outliers was assigned to these three samples. In the text, the modeled dates are rounded to the nearest half-decade since the modeled results vary from run to run.

Supplementary Materials

This PDF file includes:
Supplementary Text
Figs. S1 to S6
Tables S1 to S5

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