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From cave geomorphology to Palaeolithic human behaviour: speleogenesis, palaeoenvironmental changes and archaeological insight in the Atxurra-Armiña cave (northern Iberian Peninsula)

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ABSTRACT: A detailed geomorphological study was performed in the Atxurra-Armiña cave system (northern Iberian Peninsula) to decode landscape evolution, palaeoenvironmental changes and human use of a cave within an Inner Archaeological Context. The results show an average incision rate of the river of <0.083 mm a^{-1} for at least the last 419 ka, with interruptions due to sedimentary inputs. Moreover, allostratigraphic units comprising fluviokarstic deposits at the base and flowstone formation at the top have been shown to be climatically controlled, formed either during glacial–interglacial cycles or during interstadial cycles. Finally, when the cave was used by humans in the Late Magdalenian, the lower entrance was closed, and they must therefore have entered the cave through the upper entrance. To reach the sectors selected to decorate the panels, they probably travelled from the upper cave level, as the current crawlway was wider than today, according to our U/Th dating. Once these visitors reached the panels, the floor in the main gallery would have been around 15 cm lower than at present. However, the morphology of the conduit was similar; this has significant implications for understanding and interpreting the human use of the cave during the Palaeolithic. Copyright © 2020 John Wiley & Sons, Ltd.

KEYWORDS: allostratigraphic unit; cave processes; inner archaeological context; Palaeolithic rock art; U/Th dating

Introduction

Caves represent a harsh environment for human life, given the complete darkness, damp and usually irregular topography. Nonetheless, human populations have occupied these underground landscapes since at least the Middle Palaeolithic (Jaubert *et al.*, 2016), and particularly during the Late Palaeolithic and later Prehistoric and Historic phases. Studies of the inner archaeological context in caves are therefore of great interest, because they help to decode the behaviour and capabilities of Palaeolithic humans (Medina-Alcaide *et al.*, 2018a).

Sedimentary and erosive processes can completely change the topography of a cave over a period lasting either a few hours (Van Gundy and White, 2009) or millions of years (Laureano *et al.*, 2016). Therefore, to understand and assess the action of Palaeolithic societies within the caves, it is crucial first to understand the geological setting. For example, to analyse how they adapted and optimized the space to choose emplacements for rock art, a geological study is required to determine the original space available in the cave room (Delannoy *et al.*, 2012; Jouteau *et al.*, 2019). Most geoarchaeological studies have focused on resolving site formation processes, and taphonomic and preservation issues (Canti and Huisman, 2015). Other investigations, such as geomorphological and sedimentological studies, have centred on the evolution of the landscape (e.g. Jiménez-Sánchez *et al.*, 2002; Ortega *et al.*, 2013) and palaeoenvironmental changes (e.g. Courty and Vallverdú, 2001; Arriolabengoa *et al.*, 2018a). Although such information is very helpful in providing a broad regional context and detailed interpretation for archaeological remains, few studies have focused on the palaeotopography of the caves when they were used by ancient humans, which are indispensable for addressing issues such as the relative difficulty of the paths taken, why a particular settlement or location for different activities was chosen (Pastoors and Weniger, 2011), and whether the paths taken inside the cave – which can be determined by certain forms of archaeological remains related to underground progression (Medina-Alcaide *et al.*, 2018b) – are the same as those used at present.

The aim of this work was to integrate a detailed cave geomorphological study into a complex archaeological problem, to give a general surrounding environmental context and to further resolve human use of the caves. The study was carried out in the Atxurra-Armiña cave, located in the Cantabrian Margin (northern Iberian Peninsula). In the inner part of the upper cave level, hundreds of engraved and painted rock art figures of a Palaeolithic chronology were discovered in 2015, in addition to several archaeological remains associated with

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human frequentation in the interior of the cave (Garate *et al.*, 2016, 2020). These are located in a number of spaces that are relatively difficult to access, particularly in cornices, lateral galleries and crawlways suspended between 1 and 6 m above the current gallery floor, and in some cases, can only be reached using speleological equipment. At the same time, a preliminary geomorphological study showed that several depositional and erosive processes were identified (Arriolabengoa *et al.*, 2018b), which could have altered the known cave topography since the use of the cave by the Palaeolithic humans. To aid interpretation of the archaeological remains and human use of the cave, this study will focus on visualizing the palaeotopography of the cave conduit when it was in use (18–14k cal a BP), understanding which processes have been predominant over time, their relationship to the environmental changes in the surrounding, and the evolution of the landscape.

Context

Cantabrian Margin

The Cantabrian Margin refers to the series of valleys in the northern Iberian Peninsula running into the Cantabrian Sea (Fig. 1). It is a passive margin, uplifted by the collision between the Iberian and Eurasian plates during the Late Cretaceous–Miocene (García-Mondéjar *et al.*, 1985; de Vicente *et al.*, 2018). Despite the large area of the Cantabrian Margin, its valleys are relatively short (the longest is 159 km), and are orientated more or less at right angles to the littoral (Fig. 1).

Research carried out in different geomorphological environments has revealed an uplift rate for the Cantabrian Margin of: 0.07–0.15 mm a^{-1} for the last 1–2 million years on the Asturias coast (Jiménez-Sánchez *et al.*, 2006; Álvarez-Marrón *et al.*, 2008); 0.08 mm a^{-1} since the Late Miocene on the Basque coast (Aranburu *et al.*, 2015). The rivers are embedded and have formed a strath terrace staircase along their profile (Arriolabengoa, 2015; del Val *et al.*, 2019), inferring a general base level fall intercalated by periods of stable base level. In this regard, base level incision rates have been estimated at 0.075–0.08 mm a^{-1} (Arriolabengoa, 2015; Arriolabengoa *et al.*, 2018a) and 0.06 mm a^{-1} (del Val *et al.*, 2019), while the different cave levels described in many works appear to have originated during stable periods (Aranburu *et al.*, 2015; Ballesteros *et al.*, 2019).

Regarding prehistoric human occupation and fauna, the Cantabrian Margin is well known for its large number of archaeo-palaeontological sites (Clark *et al.*, 2019) and caves with rock art (Garate, 2014). As a result, in terms of ancient human presence, the eastern part of the Cantabrian Margin, where Atxurra-Armiña is located, has been called the 'Basque Crossroads' because it was one of the migration passages between the Iberian Peninsula and continental Europe (Arrizabalaga, 2007; Garate *et al.*, 2015). In this regard, human behaviour and activities might to some extent have been influenced by both the palaeogeography of the

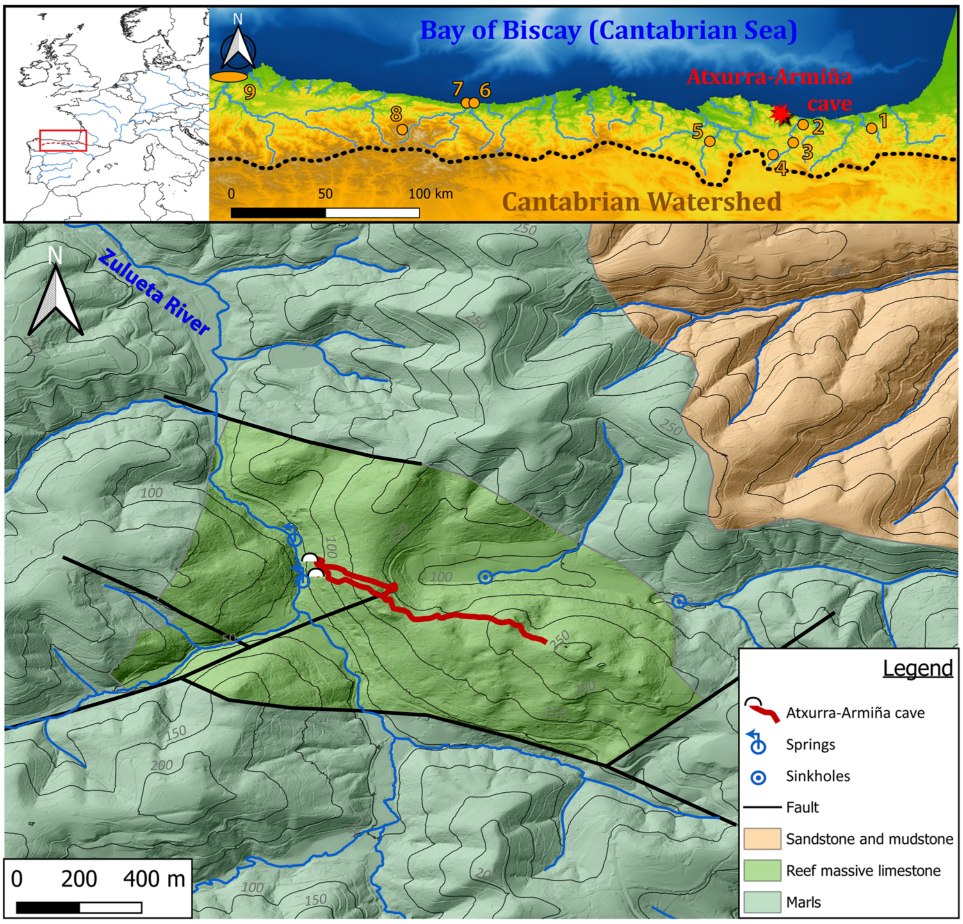

Figure 1. The upper part of the Iberian Peninsula, Cantabrian Margin, with the location of the studied Atxurra-Armiña cave and locations mentioned regarding Cantabrian Margin landscape evolution: 1, Oiartzun river terraces (del Val *et al.*, 2019); 2, Praileaitz and Urtiaga II caves (Aranburu *et al.*, 2015); 3, Deba river terraces (Arriolabengoa, 2015; del Val *et al.*, 2019); 4, Lezetxiki II cave (Arriolabengoa *et al.*, 2018a); 5, Nervion river terraces (del Val *et al.*, 2019); 6, Pindal cave (Jiménez-Sánchez *et al.*, 2006); 7, Cobiheru cave (Ballesteros *et al.*, 2017); 8, Picos de Europa caves (Ballesteros *et al.*, 2019); 9, Asturian marine terraces (Álvarez-Marrón *et al.*, 2008). Below, development of the studied Atxurra-Armiña cave system within the current landscape (geological information derived from EVE, 1986). [Color figure can be viewed at wileyonlinelibrary.com]

Cantabrian Margin and the morphology of the caves at the time when they were in use.

Atxurra-Armiña cave

The Atxurra-Armiña cave is located in the municipality of Berriatua (Biscay, Basque Country), in the valley of the Zulueta river, a tributary of the Lea, 3 km from the current coast (Fig. 1). The cave is in massive limestones from the Aptian–Albian period (EVE, 1986), mainly mudstone with corals and rudists, but also interbedded with stratified limestones with siliceous nodules, at an orientation of N150E, 20NE. The cave has two entrances situated at different altitudes above the Zulueta river (in the NE slope of the valley). The lower entrance, Armiña, is 26 m above the river bed (a.r.b.) and 55 m above sea level (a.s.l.), while the upper entrance (Atxurra) is 35 m a.r.b. and 64 m a.s.l. Both cave levels run horizontally in a NW–SE direction, parallel to a fault system (Fig. 1). At present, based on data from the ADES speleological group, the Atxurra-Armiña cave has a length of 1085 m. It is closed off at the end by sedimentary filling of the gallery and stands laterally under a small polje (Fig. 1).

In a previous study (Arriolabengoa *et al.*, 2018b), morphologies were identified developed in phreatic and vadose zones, as well as different phases of stream-related allochthonous clastic sedimentary deposits, gravitation-related autochthonous clastic sedimentary deposits and chemical sedimentary deposits. The construction of a relative stratigraphy based on cross-sections revealed various sedimentary and erosive phases, whose distribution along the cave shows three parts that have been developed at some point (Fig. 2): (i) Outer Atxurra, corresponding to the upper cave level, which runs from the Atxurra entrance to the second connection of the two cave levels; (ii) Inner Atxurra, corresponding to the upper cave level, which runs from the second connection of the two cave levels to the end of the upper cave level; and (iii) Armiña cave, which represents the entire lower cave level. A more detailed description of the cave is available in the Supporting Information.

The archaeological remains in the upper cave entrance show at least 2 m of sedimentary deposits developed during at least the last Pleistocene (Barandiaran, 1961; Fernández Eraso, 1985; Rios-Garaizar *et al.*, 2019), whereas only a few remains have been found at the entrance to the lower cave (Rios-Garaizar *et al.*, 2020). In addition, in the inner part of the Atxurra cave level, more than 100 rock art figures in the Late Magdalenian style have been found together with other archaeological remains linked to the lighting systems used by paleo-groups (scattered charcoals, hearths, etc.) and lithic tools for making art (Garate *et al.*, 2016, 2020). The rock art figures are concentrated in 19 different sectors distributed between 186 and 366 m from the Atxurra entrance (Garate *et al.*, 2020), the path to which currently includes at least one crawlway (Fig. 2).

Methods

Geomorphological and allostratigraphic units description

Significant geomorphological and sedimentological features throughout the cave were identified previously, and a relative stratigraphic scheme was generated for each part of the cave (Arriolabengoa *et al.*, 2018b). To improve the description and correlation of these features, here we expand the given details and define a relative stratigraphic column based on allostratigraphic units (sedimentary units bounded by a discontinuity, Hughes, 2010). For this purpose, we used the topography of the cave made by a 3D model created by Gim-Geomatics SL for the current project (more details in Supporting Information).

Possible location of path to rock art panels

We also focused on the rock art locations with a view to determining whether there might be more than one possible access path, currently blocked or restricted by a sedimentary body. To this end we described the location of the different rock art sectors or panels, identified whether there were different possible routes for accessing them, and determined any possible changes these paths might have undergone since their use by ancient humans. All measurements were taken using the 3D cave model. The location of archaeological remains preserved on the floor in the interior of the cave also provide significant evidence of the palaeo-path when they are in a primary position. This is the case of charcoals, probably dropped from wooden torches used by prehistoric visitors to illuminate the cave (Garate *et al.*, 2020).

Speleothem sampling, petrography and dating methodology

Having established the relative stratigraphy of the events and processes, and determined which of these might have

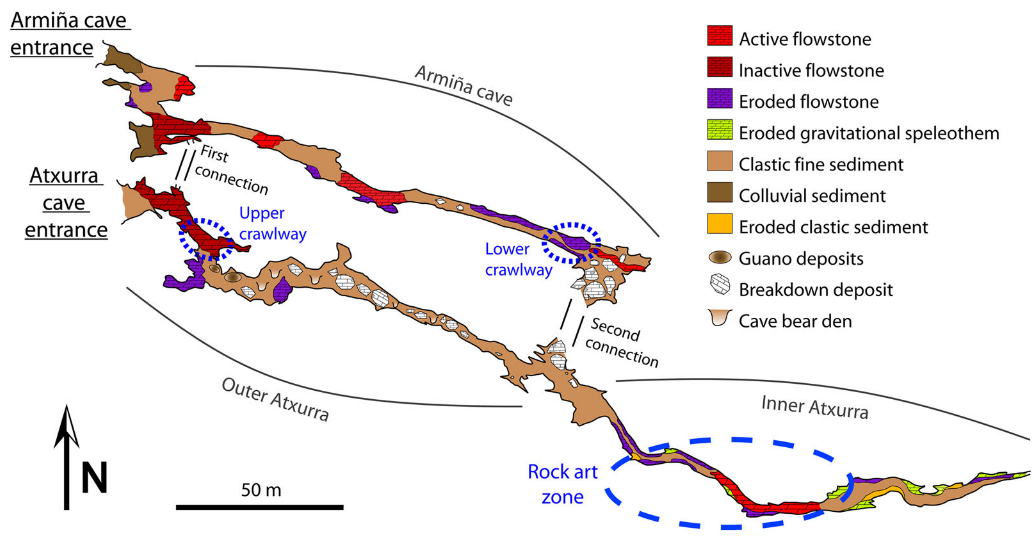

Figure 2. Topographic plan of the Atxurra-Armiña cave, showing the three parts differentiated in this work, and their different significant features. [Color figure can be viewed at wileyonlinelibrary.com]

influenced the actions of ancient humans (e.g. in selecting a 'canvas' or choosing a path), we sampled different generations of speleothems alternating in the general stratigraphy for dating by U/Th methods, to define and determine a chronology for each geological phase. Sampling, thin section and dating method details are given in the Supporting Information.

Results

Cave geomorphological and sedimentary features

By combining the different cross-section stratigraphy in each part of the cave (Arriolabengoa *et al.*, 2018b), we have developed a principal relative stratigraphic sequence for them based on allostratigraphic units (see Fig. 4).

Outer Atxurra

Most phreatic morphologies are modified by processes occurring in the vadose zone. Along the crawlway there is a ceiling channel as well as pendants, and towards the inner part of this zone these morphologies are overprinted by ceiling cupolas related to bat colonies and their guano (Fabbri *et al.*, 2017; Dandurand *et al.*, 2019). In addition, there are some vertical speleothem formations, and ceiling collapses where the cave is crossed by the stratified limestones with siliceous nodules (Fig. 3a). The only eroded sedimentary remains are an isolated relict of a flowstone 1 m in thickness, situated 2 m above the present cave floor (Figs. 3c and 4) (Arriolabengoa *et al.*, 2018b).

Its stratigraphic column consists of three allostratigraphic units (Fig. 4): the first, represented by paragenetic dissolution morphologies, is linked to a clastic sedimentary filling (now entirely eroded); the second is represented by a perched flowstone (Fig. 3c); and the third is represented by the current floor fill and the archaeological site.

Inner Atxurra

Paragenetic features are present along all the passage (ceiling channel, anastomotic bedding plane, roof pendants and horizontal notches). The sedimentary deposits, except for those on the current floor, are eroded and are relicts of clastic and chemical sediments all along the passage (Arriolabengoa *et al.*, 2018b). On the one hand, there are two relicts of centimetre-scale pebble-supported deposits at a height of 5–6 m above the floor, covered by vertically developed speleothem formations (Fig. 3e,f). These vertical speleothems – stalactites, stalagmites, columns, draperies, etc. – appear eroded along the wall of the entire passage (Fig. 3d,e). Overlying these vertical speleothems are some relics of flowstone perched at different heights, which can easily be traced in different sections of Inner Atxurra. They are mainly situated at a height of between 2–2.3 and 0.8–1 m above the current floor (Figs. 3f and 4), although there is an isolated one situated at 0.4 m (Arriolabengoa *et al.*, 2018b). Another eroded clastic deposit of rounded centimetre-scale allochthonous pebbles sometimes appears (Fig. 3d), composed of sandstone, lutites and anorthic ferruginous nodules, situated in all cases under the perched flowstones. In the middle section of Inner Atxurra, there is a vertical speleothem formation, mentioned above, covering almost the entire passage. This has been partially broken at a height of 3 m by cavers to allow further exploration of the cave deeper into the mountain, through a narrow passage. No rock art (or other archaeological remains) has been found in the cave portion beyond this gravitationally formed speleothem.

Here, the stratigraphic column is made up of at least four allostratigraphic units (Fig. 4), the first represented by paragenetic features, the second by eroded speleothems, the third by various sequences of fluviokarstic deposits at the bottom and flowstone formation at the top, and the fourth by the current passage floor.

Armiña cave level

The roof is characterized by a sinuous ceiling channel at the entrance, but is straighter towards the inner part of the cave (Fig. 3g,h). Accompanying the ceiling channel are two horizontal metre-sized notches: the upper one is visible along the entire passage (Fig. 3g,h) (Arriolabengoa *et al.*, 2018b), while the lower one is half-covered by the floor sediment in the inner part. Pendants are clearly visibly at the entrance, while towards the interior they are no more than incipient pendants (Fig. 3g). With regard to the different sedimentary processes there are many flowstone deposits perched at 1.4–1.6 and 2–2.2 m from the cave floor (Arriolabengoa *et al.*, 2018b). At the crawlway, there is a channel-shaped erosion in the flowstone that covers the floor, revealing a centimetre-scale allochthonous pebble-supported deposit below the flowstone. Because of various archaeological pits dug at the entrance, a level of fluviokarstic deposits has been found under the stratigraphic unit containing the sporadic Magdalenian occupation (Rios-Garaizar *et al.*, 2020). This level is composed of channelized centimetre- to decimetre-sized rounded pebbles of sandstones and anorthic ferruginous nodules, alternating with sandy levels. The level is at least 2 m in height, while the top is characterized by a highly irregular surface. In short, there are three allostratigraphic units (Fig. 4), the first represented by paragenetic sediments, the second by the perched speleothems and fluviokarstic deposits, and the last by the current passage floor.

Rock art panels: location and possible paths

There are 41 panels (classified using Roman numerals) arranged in 20 different sectors (classified using letters), referred to as Sector A, Panel C.IV etc. (Fig. 5; Table 1). Eight of these panels (located in Sectors A, C-floor, G′-floor, I-floor, J-floor, J′-floor and K′) are situated in the manual field accessible from the current ground level (between 0 and 1.5 m above the current passage floor). Eighteen panels (located in Sectors D′, D-floor, E′, F′, F, G′, G, H, I and J), are between 2 and 3 m above the current floor, in all cases engraved in the limestone wall rock using the roof pendants and horizontal notch morphology. Ten panels (located in Sectors C and D) are at 5.5 m above the current floor, inside a passage that runs off the main conduit. Finally, five panels (located in Sector C) are at 6.5 m above the current conduit floor, inside a passage that runs a few centimetres under the first fluviokarstic deposits (Fig. 3e).

Most of the panels have only one possible path, with variable difficulty level. However, in the case of two areas, there is another possibility. Currently, Sectors C and D are separated by a speleothem curtain that completely blocks a possible path (Fig. 6a,c). Consequently, while access to Sector D has its difficulties (there is a narrow fissure that assists a climb of 3 m in height; Fig. 6a), speleological equipment such as ropes and footholds are needed to reach Sector C (Fig. 6a,d). The other possibility is the access to Sectors H and F′ from Sector E′, whose path is blocked by a stalagmite formation (Fig. 6b). Currently, Sector F′ is accessed by climbing 3 m with the aid of ladders, while access to Sector H could be considered even more difficult, as a kind of natural 'bridge' formed by a perched horizontal flowstone (3rd allostratigraphic unit; Figs. 4 and, 6b,e)

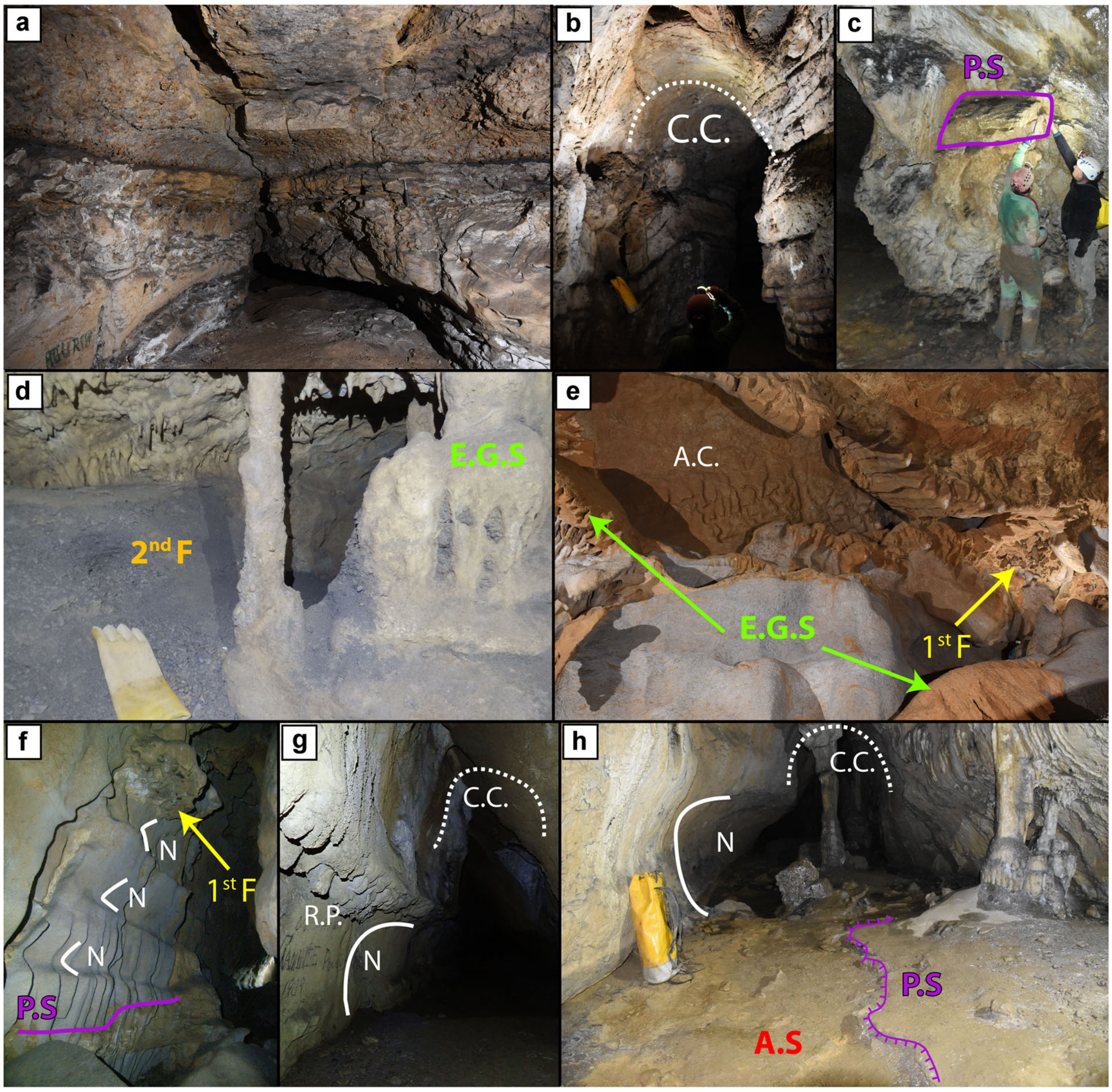

Figure 3. Photographs of different morphological features and sedimentary bodies (modified from Arriolabengoa *et al.*, 2018b). (a) Outer Atxurra: stratified and siliceous nodule conduit, where the roof has collapsed, with some collapsed blocks beneath the current soil. (b) Outer Atxurra: relict of the ceiling channel, superimposed by the vadose vertical development of the gallery. (c) Outer Atxurra: the only perched speleothem 2 m above the current cave floor. (d) Inner Atxurra, gravitational speleothem overlapped by currently eroded fluviokarstic deposits. (e) Inner Atxurra: the roof of the conduit containing anastomotic channels at the bedding plane, allocthonous fluviokarstic deposits surrounding them, eroded gravitational speleothems and roof pendant morphologies along the wall. (f) Inner Atxurra: superimposed horizontal notches, initial stage of wall roof pendants, perched flowstone at around 2 m in height from the current cave floor, and allochthonous fluviokarstic deposits near the top of the conduit. (g) Armiña cave: the ceiling channel, initial stage of roof pendants and a 1-m-wide notch. (h) Armiña cave: scarp of the flowstone, being filled by the current active flowstone. Abbreviations: A.C, anastomotic channel; C.C, ceiling channel; E.G.S, eroded gravitational speleothem; 1st F, fluviokarst before gravitational speleothem; 2nd F, fluviokarst after speleothem formation; N, notch; R.P, roof pendant; P.S, perched speleothem. [Color figure can be viewed at wileyonlinelibrary.com]

has to be crossed to reach a ledge more than 3 m above the passage floor in the face of Sector F′. There might have been be a relatively easier path (with progressive climbs) to reach these sectors, using a crawlway connecting Sectors E′ and F′, currently blocked by a stalagmitic formation (Fig. 6b).

Speleothem samples, petrology and dating

Overall, 12 samples were taken to corroborate the stratigraphic schemes and possible human paths, based on the characteristic described in Table 2. Sampling for dating was performed in the translucent layers, with the exception of ATX-15, which has a dendritic fabric. General petrographic descriptions are given in Table 2 and microphotographs are available with the Supporting Information. Sample ATX-11 had clastic sediments within some layers, and ATX-10 probably underwent diagenetic processes, and was a product of dissolution and re-precipitation of a primary calcite (Frisia, 2015). Sample ATX-2 has two very different fabrics; however, sampling was taken from the open columnar fabric. The remaining samples are in principle primary crystals and do not appear to have undergone any diagenetic or alteration processes.

The results of the speleothem dating are given in Table 3. The U concentration of the samples is relatively very low (10–50 p.p.b.); some have high ^{232}Th and low ^{230}Th/^{232}Th ratios (ATX-1, ATX-11 and ATX-15). ATX-11 contains clastic particles, and ATX-15 does not have a translucent crystal lamina, and those results may therefore have major errors.

Discussion

Cave formation and landscape evolution

Both cave levels initially developed under phreatic/epiphreatic conditions, with morphologies related to paragenetic

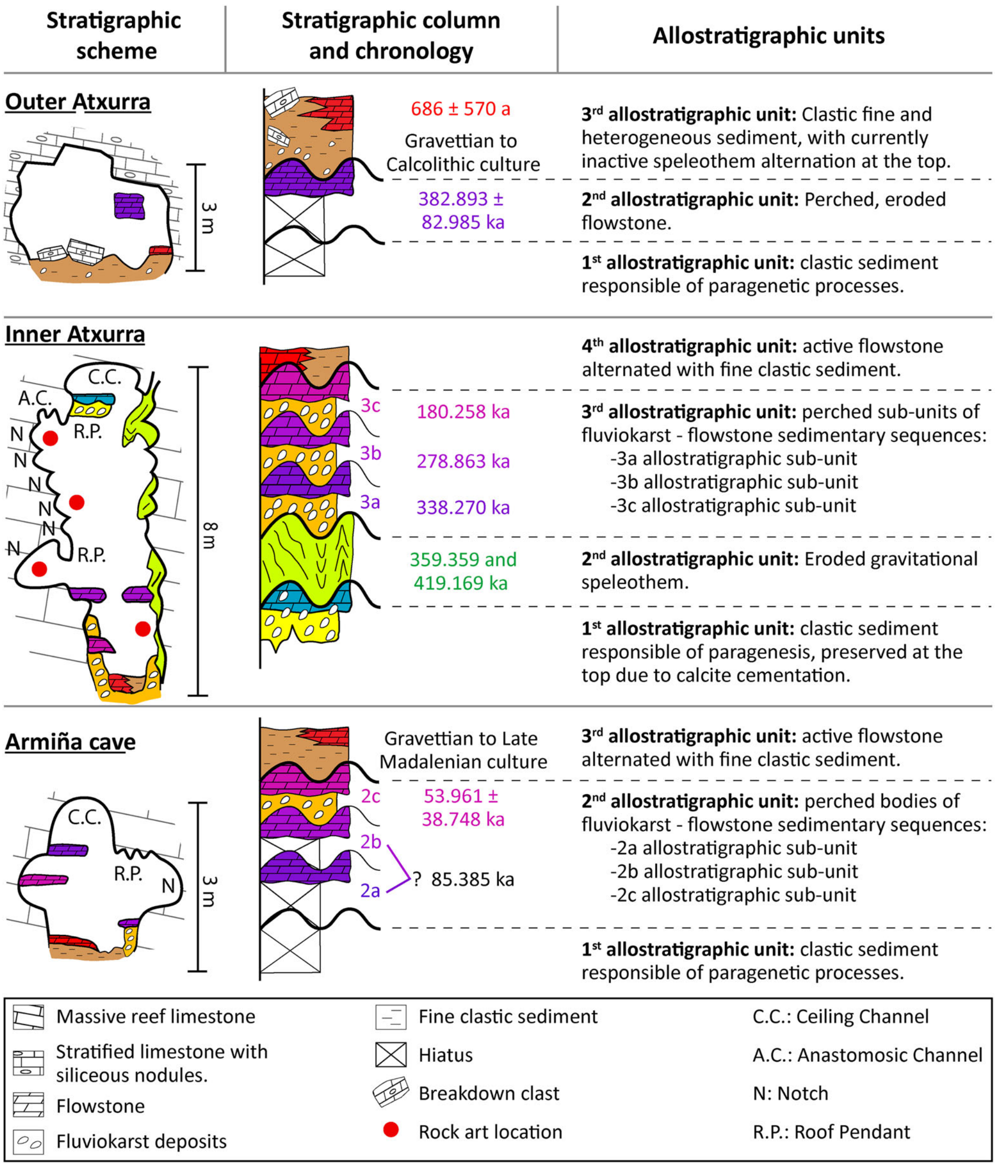

Figure 4. The overall stratigraphy of the three parts of the cave (stratigraphic scheme modified from Arriolabengoa *et al.*, 2018b). [Color figure can be viewed at wileyonlinelibrary.com]

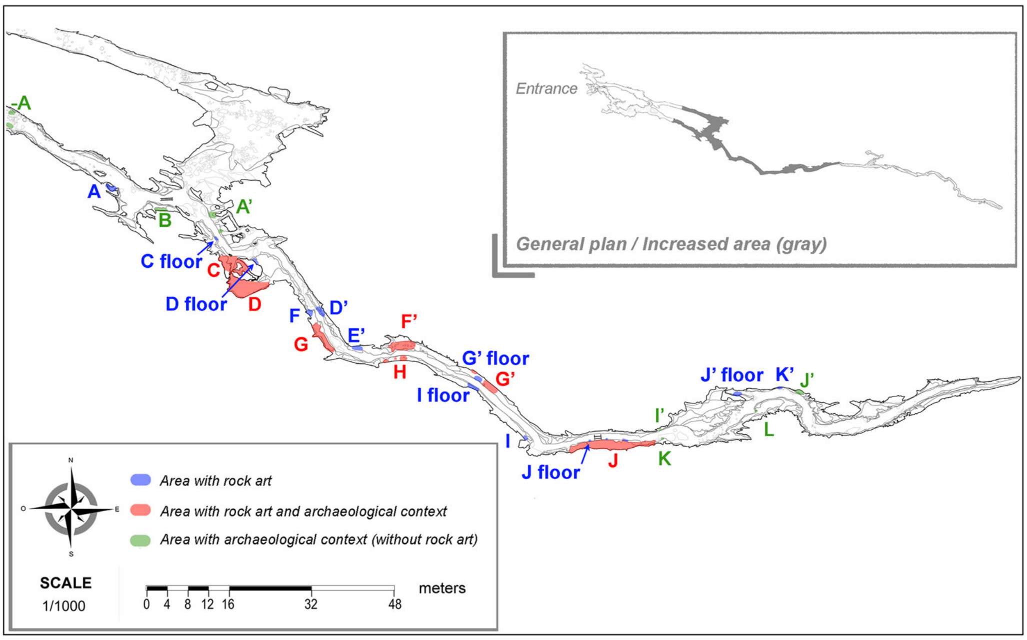

Figure 5. Location of the 19 different rock art sectors and the archaeological context (modified from Garate *et al.*, 2020). [Color figure can be viewed at wileyonlinelibrary.com]

Table 1. All panels with rock art in Atxurra cave, showing their location, and their height above the floor.

Sector	Panel	Height (m)	Sector	Panel	Height (m)
A	I	0.0	F	I	3.5
C	I	5.5	F′	I	4.0
C	II	6.5	F′	II	4.0
C	III	6.5	F′	III	4.0
C	IV	6.5	F′	IV	4.0
C	V	6.5	F′	V	4.0
C	VI	6.5	F′	VI	4.0
C-floor	I	1.5	G	I	2.5
D	I	5.5	G	II	2.5
D	II	5.5	G	III	2.5
D	III	5.5	G′	I	2.5
D	IV	5.5	G′-floor	I	1.5
D	V	5.5	H	II	4.0
D	VI	5.5	I	I	4.0
D	VII	5.5	I-floor	I	1.5
D	VIII	5.5	J	I	2.5
D	IX	5.5	J	II	3.0
D′	I	2.5	J′-floor	I	1.5
D′	II	2.5	J-floor	I	1.5
D-floor	I	3.0	J-floor	II	1.5
E′	I	3.0	K′	I	1.5

processes (Arriolabengoa *et al.*, 2018b). While paragenetic growth implies that relatively more sediment is deposited than the stream can discharge, horizontal notches on the conduit wall are related to stable periods in the sediment/stream ratio (Pasini, 2012). Given that both cave levels are relatively horizontal, with no significant slopes, and have very continuous horizontal notches in parts of the caves where they are visible, our interpretation is that both cave levels are close to representing the ancient base-level (Farrant and Smart, 2011) (Fig. 7). The oldest dated speleothems were formed after the erosion of the paragenetic sediment in the Inner Atxurra part (419.169 ± 18.126 ka); because the upper cave level formation pre-dates this speleothem, we have a minimum base-level fall rate of 0.083 mm a^{-1} for the Zulueta river valley. This rate is consistent with tectonic uplift rates obtained from littoral (Álvarez-Marrón *et al.*, 2008; Aranburu *et al.*, 2015) and fluvial (Arriolabengoa, 2015; Arriolabengoa *et al.*, 2018a; del Val *et al.*, 2019) records, which could attest to a similar behaviour of tectonic and base-level lowering rates throughout the Cantabrian Margin. However, because the dated speleothem in Atxurra-Armiña is posterior to the water table, the base-level lowering rate should be considered lower in this case.

The oldest speleothem date obtained in the lower cave level does not correspond to the period during which the cave level

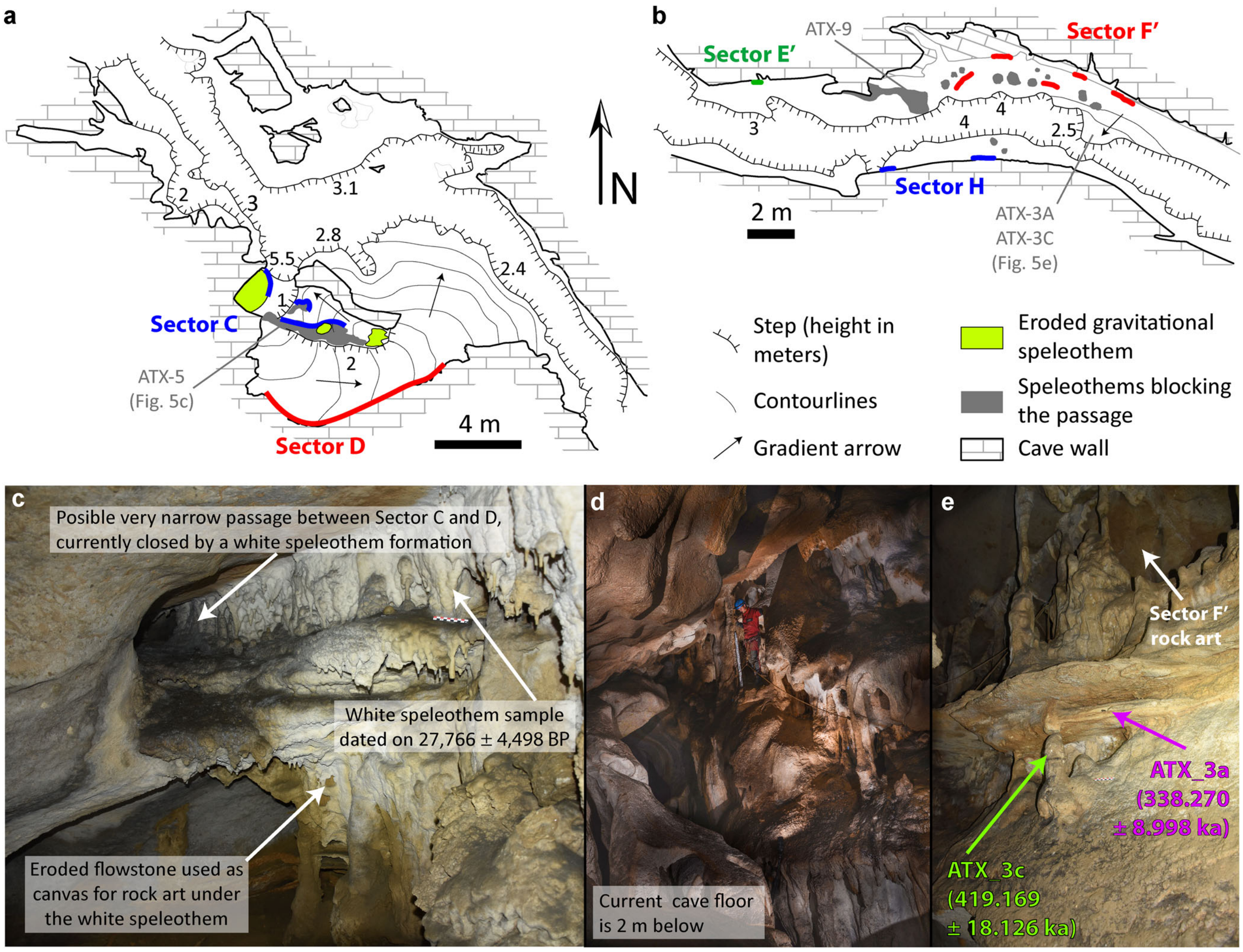

Figure 6. (a) Detailed topography and location of Sectors C and D. (b) Detailed topography and location of Sectors E′, F′ and H. (c) Photograph of the speleothem formation blocking the path from Sector D to C and the speleothem sample (ATX-5) taken to date the curtain. (d) Location of the 5.5-m vertical step currently used to access Sector C. (e) The 'bridge' affording access to Sector H from Sector F′, which is a third allostratigraphic unit that has been sampled (ATX-3A). Below is a gravitationally formed stalagmite belonging to the second allostratigraphic unit that has also been sampled (ATX-3C). [Color figure can be viewed at wileyonlinelibrary.com]

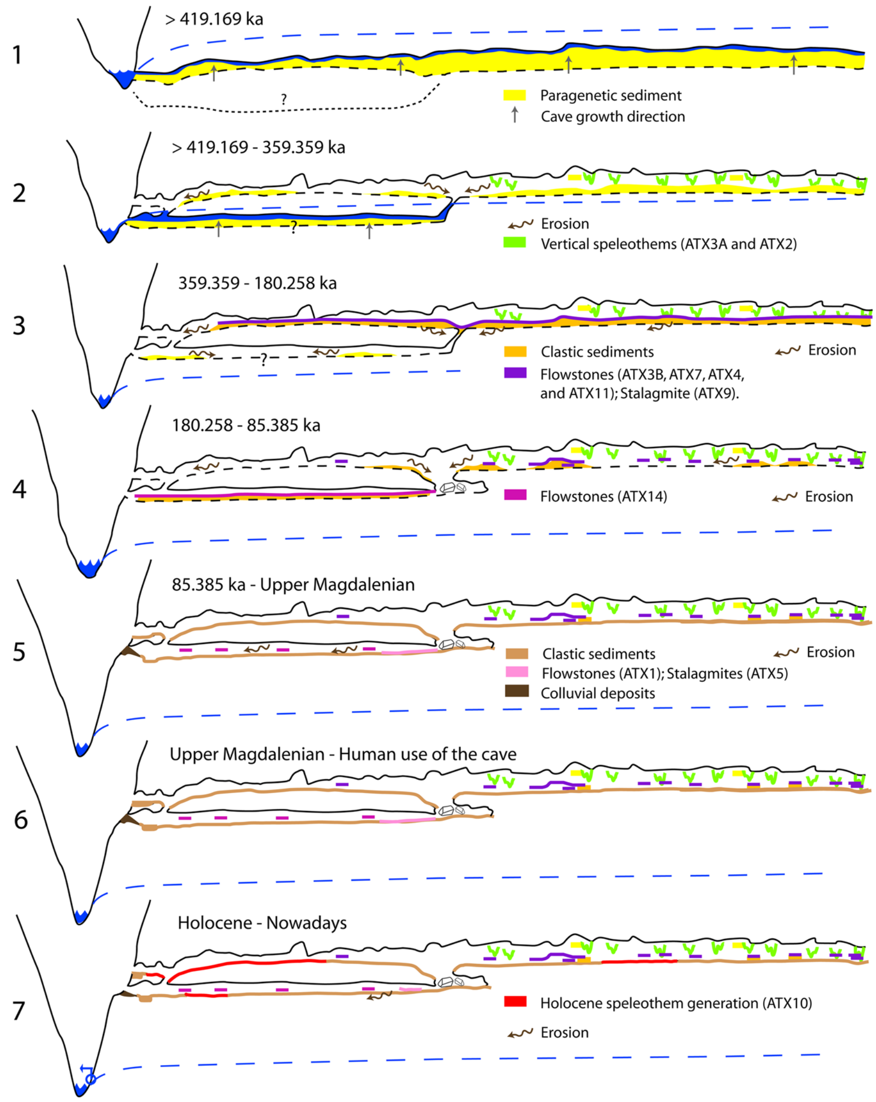

Figure 7. Cave and landscape evolution. (1) Enlargement of the upper conduit by paragenetic processes. (2) First erosion phase and vertical speleothem formation in the upper cave level. Part of the eroded paragenetic sediment is probably entrained into the lower cave level, concurring in its enlargement through paragenetic processes. (3) During this period in the upper cave level, various allostratigraphic units were deposited, consisting of a fluviokarstic deposit at the bottom, flowstone formation at the top and an erosive surface ending the sequence. These units were formed both during interglacial–glacial cycles and in interstadial climatic cycles. (4) While in the upper cave level, mainly erosive processes occur, in the lower cave level the first allostratigraphic unit was deposited. (5) Erosive processes continued in the upper cave level, while in the lower level there were also sedimentation phases creating allostratigraphic units. (6) During human use of the cave, the lower cave level entrance was closed by colluvial deposits, the crawlway of the same level was similar to the present, while the upper level crawlway was larger. (7) Speleothem formation and some inner fluviokarstic processes have caused only minor changes to the cave floor. [Color figure can be viewed at wileyonlinelibrary.com]

was formed by paragenesis. Nevertheless, if we use the base-level lowering rate obtained previously, we can estimate that the lower cave level was formed before about 215.8 ka. During this period (338.270 ± 8.998 to 180.258 ± 5.225 ka), the upper cave level was developing under vadose conditions, as indicated by different intercalated sedimentary sequences consisting of erosive phases (sub-units of the third allostratigraphic unit; Fig. 4), alluvial deposits and flowstone formation. These sedimentary sequences in the upper cave level were probably related to flooding episodes, when the lower cave level was not able to discharge all the water (Gabrovšek *et al.*, 2014) and sediment. In this regard, the Atxurra-Armiña cave shows that rates of sediment input do greatly influence the 'competition' between formation of a canyon (upper cave level) and evolution of looping pathways (lower cave level) (Gabrovšek *et al.*, 2014). On the one hand because canyon incision would stop during fluviokarstic sedimentation periods in the upper cave level, and on the other, because erosive processes and canyon incision are dominant in the upper cave level, these erosive processes might provide more sediment to the lower cave level, facilitating paragenesis and therefore formation of the lower cave level.

Regarding landscape evolution, the Atxurra-Armiña cave shows that base-level fall was not constant, with periods with a relative increase in sediment input, and therefore the valley and water table caves develop upward instead of entrenching (Fig. 7). A similar situation of base-level incision and stable periods has been described for strath terrace staircases in the region, suggesting that they belong to glacial–interglacial Quaternary climate cycles (Arriolabengoa, 2015), and not to the effects of changes in sea level per se. Although it has yet to be proved by dating (del Val *et al.*, 2019), this study supports the hypothesis that this stabilization of the base level is due to an increase in sedimentary input related to environmental conditions (see below), and not to a rise in sea level (Aranburu *et al.*, 2015), which for the last highstand of Marine Isotope

Table 2. Sampled speleothems: context, macroscopic appearance and microfabric. Description based on Frisia *et al.* (2000) and Muñoz-García *et al.* (2012).

Sample	Location	Context	Macroscopic appearance	Microfabric
ATX-1	Armiña cave level	2-cm-thick eroded and slightly perched flowstone that covers centimetric pebbles. It currently forms a crawlway complicating human access along this path.	Translucent to milky opaque and porous. Lamination is visible.	Open columnar fabric.
ATX-2	Inner Atxurra	Eroded vertical speleothem located 20 cm above the current floor. Because the core (4 cm in diameter) shows completely altered crystals while the exterior is very crystalline (3 cm long), the sample for dating has been taken from the exterior. The speleothem therefore started forming before the date given.	The core is corroded, brown, opaque and porous, with a blurred lamination. The external part is translucent with blurred lamination.	Degraded dendritic fabric and good preserved columnar fabric (Fig. S1a).
ATX-3A	Inner Atxurra	Eroded flowstone at 2.3 m above the current floor. The sample was taken from the base of the perched speleothem that is at least 30 cm thick (Fig. 6e). Therefore, the dating will correspond to the start of the flowstone formation.	Translucent to milky, with a fine and regular lamination.	Columnar microcrystalline with growth lamination (Fig. S1c).
ATX-3C	Inner Atxurra	Eroded vertical speleothem embedded in ATX-3A perched flowstone (Fig. 6e).	Translucent with a blurred lamination.	Open columnar fabric.
ATX-4	Inner Atxurra	Eroded flowstone at 0.4-m height from the current floor. The sample was taken from the top of a flowstone of at least 20 cm, which at the same time is intercalated by fine clastic laminae. The result will provide the age of the end of the speleothem flowstone.	Translucent with a blurred lamination.	Open columnar fabric and columnar microcrystalline.
ATX-5	Inner Atxurra	Inactive stalagmite that blocks the path between Sectors C and D (Fig. 6a,c). It is covering another eroded gravitational flowstone used for canvas by ancient humans, and its age will show whether the path might have been open when the Magdalenian groups frequented the cave.	Translucent to milky opaque, with a fine regular lamination	Open columnar fabric (Fig. S1b) and some mosaic calcite.
ATX-7	Inner Atxurra	Eroded and perched flowstone at 1.1 m from the current floor. The sample was taken at the top of a flowstone 5–10 cm thick. Therefore, dating will provide the last age of the flowstone.	Translucent with a visible lamination.	Open columnar fabric.
ATX-9	Inner Atxurra	Currently, eroded vertical speleothem located at the notch at 1 m depth. It blocks the path between Sectors E′ and F′ (Fig. 6b), so its age will show whether this pass was still blocked when the Magdalenian groups frequented the cave.	Translucent with a fine regular lamination.	Open columnar fabric.
ATX-10	Outer Atxurra	Inactive gours-flowstone covering the floor in the crawlway. The sample was taken from the top, and therefore its age will show whether the flowstone was there when the Magdalenian groups used the passage.	Translucent to milky opaque with a blurred lamination and porous.	Mosaic sparite crystals with high porosity and no evidence of former aragonite needles (Fig. S1e,f).
ATX-11	Outer Atxurra	Eroded and perched flowstone at 2 m height above the current floor (Fig. 3c). The sample was taken from the middle of flowstone of at least 0.7 m thickness. Very poorly preserved crystals. However, because it was the only perched flowstone at this level in this part of the cave, we decided to test it.	Brown, opaque, porous with some translucent layers showing fine lamination.	Degraded dendritic fabric with some quartz and clay mineral laminae (Fig. S1d).
ATX-14	Armiña cave level	Eroded and perched flowstone at 1.6 m height above the current floor. The sample was taken from the top of flowstone of at least 30 cm in thickness, and its age will therefore reflect the end of the flowstone formation.	Translucent to milky opaque with fine lamination.	Open columnar fabric.
ATX-15	Armiña cave level	Flowstone covering one of the colluvial deposits filling the entrances. It is a 1-cm-thick flowstone with poor crystallization. However, we decided to test it to determine when the conduit was closed.	Milky opaque and porous with blurred lamination.	Dendritic fabric.

Table 3. ^{230}Th dating results.

Sample number	^{238}U (p.p.b.)	^{232}Th (p.p.t.)	^{230}Th/^{232}Th (atomic × 10^{-6})	δ^{234}U* (measured)	^{230}Th/^{238}U (activity)	^{230}Th age (a) (uncorrected)	^{230}Th age (a) (corrected)	$\Delta^{234}U_{initial}$† (corrected)	^{230}Th age (a BP)‡ (corrected)
ATX-1	39.1 ± 0.1	109 737 ± 2198	7 ± 0	906.2 ± 3.1	1.2272 ± 0.0059	101 448 ± 785	54029 ± 38748	1055 ± 114	53961 ± 38748
ATX-2	18.1 ± 0.0	1165 ± 23	293 ± 6	137.2 ± 2.6	1.1416 ± 0.0051	360 794 ± 13 234	359427 ± 13 115	378 ± 16	359359 ± 13115
ATX-3A	12.8 ± 0.0	3647 ± 73	93 ± 2	504.3 ± 2.6	1.6019 ± 0.0072	341985 ± 8864	338338 ± 8998	1310 ± 34	338270 ± 8998
ATX-3C	10.0 ± 0.0	2267 ± 45	120 ± 2	495.6 ± 3.4	1.6458 ± 0.0080	421773 ± 18 385	419237 ± 18126	1618 ± 84	419169 ± 18126
ATX-4	12.1 ± 0.0	10743 ± 215	23 ± 0	264.4 ± 4.3	1.2577 ± 0.0082	296 415 ± 10068	278931 ± 15335	581 ± 27	278863 ± 15335
ATX-5	21.2 ± 0.0	6637 ± 133	21 ± 0	446.9 ± 3.4	0.3946 ± 0.0042	34139 ± 435	27834 ± 4498	483 ± 7	27766 ± 4498
ATX-7	19.3 ± 0.0	7084 ± 142	55 ± 1	409.4 ± 3.1	1.2306 ± 0.0063	186862 ± 2526	180326 ± 5225	681 ± 11	180258 ± 5225
ATX-9	11.1 ± 0.0	2067 ± 41	147 ± 3	698.3 ± 6.2	1.6676 ± 0.0105	235 695 ± 5070	233361 ± 5243	1349 ± 23	233293 ± 5243
ATX-10	31.8 ± 0.0	1084 ± 22	9 ± 1	318.5 ± 2.7	0.0181 ± 0.0024	1509 ± 200	754 ± 570	319 ± 3	686 ± 570
ATX-11	40.2 ± 0.1	221 271 ± 4437	5 ± 0	505.5 ± 3.3	1.6801 ± 0.0112	470 607 ± 34 492	382961 ± 82 985	1490 ± 339	382893 ± 82 985
ATX-14	59.8 ± 0.1	6236 ± 125	127 ± 3	404.6 ± 2.1	0.8007 ± 0.0027	87 472 ± 476	85453 ± 1503	515 ± 3	85385 ± 1503
ATX-15	52.7 ± 0.1	60 011 ± 1203	5 ± 0	233.4 ± 2.3	0.3368 ± 0.0037	34 407 ± 445	3920 ± 22 517	236 ± 15	3852 ± 22 517

The error is 2σ. U decay constants: λ238 = 1.55125 × 10 − 10 (Jaffey *et al.*, 1971) and λ234 = 2.82206 × 10 − 6 (Cheng *et al.*, 2013). Th decay constant: λ230 = 9.1705 × 10 − 6 (Cheng *et al.*, 2013).
*$\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$.
† $\delta^{234}U_{initial}$ was calculated based on ^{230}Th age (T), i.e. $\delta^{234}U_{initial} = \delta^{234}U_{measured}\, e^{\lambda 234 \times T}$. Corrected ^{230}Th ages assume the initial ^{230}Th/^{232}Th atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. These are the values for a material at secular equilibrium, with the bulk earth ^{232}Th/^{238}U value of 3.8. The errors are arbitrarily assumed to be 50%.
‡ BP stands for 'Before Present' where 'Present' is defined as 1950 AD.

Stage (MIS) 5e was around the current sea level in the Cantabrian Margin (Ballesteros *et al.*, 2017).

Palaeoenvironment insights

Once vadose conditions had been reached, the conduits continued to evolve, and their development reflects changes in palaeoenvironmental conditions (Fig. 8). Based on the stratigraphy of the different parts of the cave, different phases of speleothem formation, of fluviokarstic growth, and erosion have been recorded (Arriolabengoa *et al.*, 2018b).

In Inner Atxurra, vadose conditions began before 419.169 ± 18.126 ka, with the erosion of the paragenetic sediment, leaving space for the formation of the 2nd allostratigraphic unit. These are gravitational-type speleothems (ATX-2 and ATX-3C), formed at least between MIS11e-c and MIS10c. Therefore, their precipitation occurred during MIS11 (Fig. 8), probably with interruptions, while the position of the cave floor is unknown; however, based on the position of Sample ATX-2 it was no more than 20 cm above the present level.

Following the formation of the 2nd allostratigraphic unit, the first fluviokarstic deposition occurred in the period from MIS10a to MIS9e, as the perched flowstone is dated at 338.270 ± 8.998 ka. This is located 2.3 m above the current floor (ATX-3A), embedding the formation of ATX-3C (Fig. 6e). Therefore, the Atxurra-Armiña cave confirms the hypothesis of fluviokarstic aggradation in the Cantabrian Margin due to glacial to interglacial changes (Aranburu *et al.*, 2015; Arriolabengoa, 2015) (Fig. 8).

The next erosion occurs after MIS9e, after which a new allostratigraphic sub-unit (3b; Fig. 4) is formed until 278.863 ± 15.335 ka (ATX-4). Therefore, the erosion occurred during the interglacial–glacial transition, again validating the previous hypothesis; however, it also demonstrates not only that flowstone formation occurred during optimal climate periods, but also that these allostratigraphic units were deposited during less optimal conditions such as interstadials (Fig. 8).

There is a gap of almost 100 ka (Fig. 8) until the next identified allostratigraphic sub-unit. During this time speleothem formations such as stalagmite ATX-9 grew; however, we were unable to identify any allostratigraphic sub-unit. This might mean that it did not occur, that it has not been identified and dated, or that it is below the present floor. The last identified sequence of erosion – fluviokarst deposition – flowstone formation occurred at least before MIS6e, confirming that other periods or smaller climatic cycles, such as interstadials, could also have developed this type of sequence.

After MIS6c, no other allostratigraphic unit was recorded in Inner Atxurra, except for that represented by the current floor, which is still forming in some parts (flowstone alternating with fine sedimentation). For Outer Atxurra, the location of flowstone ATX-11, 2 m above the current floor, indicates that it might be correlated to one of the perched flowstones identified in Inner Atxurra. However, dating to 382.893 ± 82.985 ka makes it impossible to determine to which one it might be related. Regardless, it must have been before full opening of the connection between the Inner Atxurra and Armiña cave level (Fig. 7).

No allostratigraphic phases related to paragenesis were identified in the lower cave level (Armiña level; Fig. 4). The first speleothem we have from the level is ATX-14, with an age of 85.385 ± 1.503 ka, which is the end of a thick flowstone. During this period the gallery was already formed and had been eroded once, and therefore this flowstone formed during MIS5, and the previous fluviokarstic deposition could probably

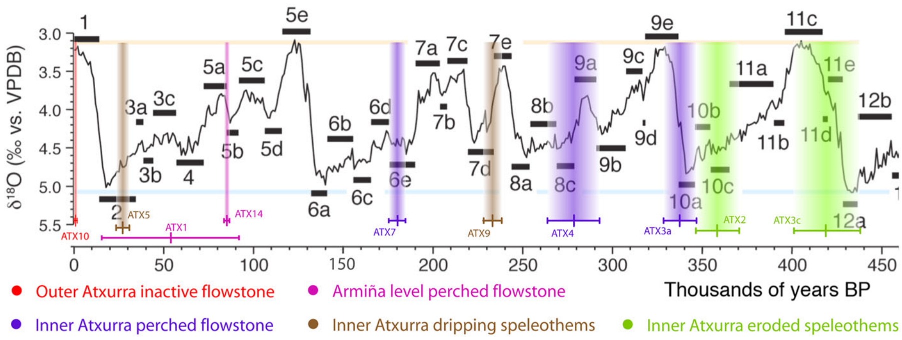

Figure 8. Growth of speleothems in the Atxurra-Armiña cave system based on samples from this work, and their relationship to palaeoenvironmental changes (figure modified from Railsback *et al.*, 2015). [Color figure can be viewed at wileyonlinelibrary.com]

have occurred around MIS6. This sequence ended with an erosive process, and a new sequence began with flowstone at the top, although its date of 53.961 ± 38.748 ka does not allow any thorough interpretation (Fig. 8).

Previous studies along the Cantabrian Margin have highlighted the correlation between cave processes and palaeoenvironmental changes during glacial–interglacial cycles since MIS9 (Jiménez-Sánchez *et al.*, 2006; Stoll *et al.*, 2013; Aranburu *et al.*, 2015; Ballesteros *et al.*, 2017, 2019; Arriolabengoa *et al.*, 2018a). They support the general idea that interglacial periods are relatively favourable for speleothem formation, interglacial–glacial transitions are quite suitable for erosive processes, and glacial–interglacial transitions are relatively important for fluviokarstic processes (Arriolabengoa, 2015). The results shown in Atxurra-Armiña cave reinforce this argument, and it extends it until the MIS12–11 transition. Recently, Ballesteros *et al.* (2019) defined four speleothem generation stages since MIS9 in the Picos de Europa karstic massif. Except for the current speleothem generation, the end of these speleothem generations occurs as they approach the maximum glacial in each stage, whereas most of them are cut down by incision. Although the type of karst is different, the speleothem generation stage proposed by Ballesteros *et al.* (2019) matches relatively well with the speleothems within allostratigraphic units and sub-units of Atxurra-Armiña. Therefore, the generic cave processes and their response to environmental changes could be relatively alike along the Cantabrian Margin. Additionally, allostratigraphic units and sub-units in Atxurra-Armiña cave suggest that whether glacial–interglacial cycles have the greatest effcet on cave processes, interstadial cycles could disrupt the cave morphology.

Archaeological implications

The rock art panels and their associated archaeological remains are located in Inner Atxurra, on hanging ledges and passages (formed by notches) at different heights above the current floor (Figs. 4 and 6) (Garate *et al.*, 2020). This concealed location of the paintings and engravings suggests that access for Palaeolithic human groups was remarkably difficult, even requiring dangerous manoeuvres (such as climbing with a notable risk of falling). Both cave entrances contain archaeological remains; however, while at the Atxurra entrance there is a continuous record with remains from different periods over at least the last 30 000 years (Rios-Garaizar *et al.*, 2019), in Armiña there is evidence of only sporadic occupation (Rios-Garaizar *et al.*, 2020). Dating of the speleothem covering the colluvial deposits in the Armiña entrance (ATX-15) gave an invalid result; however, the presence of only sporadic occupation, the features (it appears unrelated to technological and subsistence activities) and the absence of allochthonous sediments carried in from the nearby entrance indicate that the lower entrance was closed during the Late Magdalenian (Rios-Garaizar *et al.*, 2020).

Consequently, considering our geomorphological and palaeoenvironment study, we can affirm that Palaeolithic artists entered the cave using the Atxurra cave entrance (the natural entrance to the upper level), and that to reach the decorated sectors (located in the Inner Atxurra zone), they would have had to walk through the Outer Atxurra zone or first descend to the Armiña cave level (using the first connection shaft) and then ascend to the upper-level using the second connection. Both paths are relatively ‘easy’, except for their respective crawlway zones. The age of 686 ± 570 years given for the gours-type flowstone ATX-10 covering the current soil of the upper-level crawlway indicates that this speleothem (or much of it, at least) was not present during the Late Magdalenian (13 000–11 700 uncal a BP). We found the flowstone to be 15–30 cm in thickness, located within thin fluviokarstic sediments with some scattered charcoal below them and thus demonstrating that the upper crawlway was easier to transit in the period during which the inner part of the cave was decorated. By contrast, the age of 53.961 ± 38.748 ka given by the flowstone that forms the lower level crawlway (although the resolution is very poor) is from before the Magdalenian period; therefore, this was as wide as it is at present. It therefore seems plausible that they would have preferred the upper path to the lower (longer and narrower) one.

With regard to access to the decorated panels, some of them are very difficult (and quite dangerous) to reach, requiring vertical climbs. However, they might have been reached using possibly easier paths that are now blocked by speleothems. The dating of those speleothems supports the hypothesis that those routes were already blocked when the cave was frequented in prehistoric times (during the Late Magdalenian). For the possible path from Sector C to Sector D it was closed at least 27.766 ± 4.498 ka ago, and for the path from Sector E′ to Sector F′, at least 233.293 ± 5.243 ka ago. Regarding the floor, the developing flowstone is at most 15 cm thick, which would not have significantly changed the current morphology of the passage. There are some engraved panels at a height of 0.5 m, so we can see that the Palaeolithic floor was close to the current one (probably at least 15 cm lower).

These observations have been partially confirmed by the archaeological study of these possible paths: some conserve remains of scattered charcoals in a primary position, indicating prehistoric transit along these routes. This is the case of the current access to Sector C, where some scattered charcoal remains have been found on the path used. The same occurs in Sector H, where the prehistoric path is confirmed by the presence of scattered charcoals along the current path. An anthracological study has shown that these charcoals correspond to oak and juniper woods, species that grew in the area around the Atxurra cave at least from the Late Paleolithic (Garate *et al*., 2020).

Finally, in the middle part of the inner zone of Atxurra, there is a gravitational speleothem formation that separates the decorated area of the cave from the last part of the gallery. No archaeological remains have been found in this final part of the cave, and we therefore believe that this formation might have blocked the path to the Magdalenian groups (forming a very difficult narrowing in this part). This formation belongs to the eroded vertical formation phase of the inner part of Atxurra (2nd allostratigraphic unit), and was therefore formed at least 359.359 ka ago, and the small window that connects the two parts of the gallery was probably made by cave visitors during the mid-20th century (remains from the operation can still be seen today).

Conclusions

By making a detailed geomorphological study of the Atxurra-Armiña cave system, we were able to elucidate information on the evolution of the landscape throughout the Cantabrian Margin and alterations in processes in the karst system related to environmental changes, which help us to understand the surrounding environment frequented by humans since the Middle Pleistocene. Moreover, by simulating the palaeotopography of the cave from the time of human usage in the Late Magdalenian, we were able to determine the partial influence of cave morphology on their activity.

Thus, U/Th dating of the allostratigraphic units shows that the average incision of the Zulueta river was $<0.083\ \mathrm{mm\ a^{-1}}$ giving a similar incision rate to other valleys situated in the Cantabrian Margin, and was interrupted by periods in which discharge was unable to entrain the entire sediment load, leading to sedimentation in the cave, and consecutively to paragenetic processes. In terms of palaeoenvironmental changes, this study shows that allostratigraphic units also developed during interstadial-scale cycles during the Middle and Late Pleistocene, rather than only during glacial–interglacial cycles. Most of the speleothems were formed in the interglacial period, while none of them is recorded as having been formed during the maximum glacial periods. Finally, because of these geological processes and the evolution of the cave, we know that the Late Magdalenian artists entered the cave using the upper entrance, and may have used the upper cave level rather than the lower one (we know that they also frequented that area) to reach the canvases in the inner part of the upper cave level, which would have been in practically the same condition as today. More confident archaeological interpretations of human use of the Atxurra-Armiña cave can now be made because we have a more precise knowledge of its palaeotopography and the way the cave operates with regard to environmental changes. In conclusion, integration of a geomorphological cave study has been shown to be an excellent instrument for addressing and resolving inter- and multidisciplinary issues, and should be used more widely in different archaeological contexts to increase accuracy in the interpretation of human behaviour.

Supporting information

Additional supporting information may be found in the online version of this article at the publisher's web-site.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Abbreviations. a.r.b., above the river bed; a.s.l., above sea level; MIS, Marine Isotope Stage.

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