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Carbonate microfacies reveal how Asturian shell middens formed in the Mesolithic☆

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ABSTRACT

The littoral platform of eastern Asturias (northern Spain) is a coastal karst modeled by the sea. During the Early Holocene, this landscape was exploited by successfully coastal-adapted hunter-gatherers. Intense coastal foraging resulted in accumulation of large amounts of shellfish in numerous karstic rockshelters. A century ago, the Count of Vega del Sella established the post-Paleolithic age of the Asturian shell middens, carbonate-cemented deposits hanging from the walls of karstic cavities. He argued that these were remnants from past shell accumulations filling up completely the rockshelters, as result of direct waste disposal, while the occupations occurred outside. Our geoarchaeological approach tested this long-lasting site-formation model with micromorphology and carbonate microfacies analysis of two sites: El Alloru and El Mazo. Novel outcomes are: 1) the carbonate cements correspond to calcareous tufa resulting from spring activity; 2) the deposits show a stratigraphic framework related to successive phases of debris accumulations and stasis; 3) tufa formation and accumulation of anthropogenic debris are syn-depositional; 4) biogenic and diagenetic cements reveal phreatic conditions. All these contradict a priori expectations from Vega del Sella's widely accepted model of anthropogenic mound constructions preserved in the currently cemented deposits. Microcontextual evidence suggest that shells were likely processed and produced also inside the rockshelters, which might have been used as occupation spaces as well instead of just for waste disposal, while the analyses exterior deposits at El Alloru also present occupational signs. This study also supports further evidence for higher water-table levels in the early Holocene at regional level, despite most caves show no signs of spring activity today.

1. Introduction

The image reproduced in Fig. 1 was published exactly one hundred years ago from when the first draft of this paper was written. It shows how the numerous prehistoric shell middens found in the karstic cavities at the littoral platform of Asturias (northern Spain) formed, according to the pioneer prehistorian Count of Vega del Sella (1923). This model of site formation processes results from Vega del Sella's previous surveys (Vega del Sella, 1914; Vega del Sella, 1916) searching for understanding the context of the novel Asturian lithic industry he had discovered. The Count's awareness regarding archaeological site-formation and stratigraphy prompted his model to become a paradigm for interpreting archaeological record of the Mesolithic in the Asturian area where, by the way, one of the highest densities of archaeological sites in western Europe is known (Gutiérrez-Zugasti et al., 2011). In the present paper, the model is tested using a geoarchaeological approach.

Understanding context is essential to assess chronological, functional, and post-depositional biases of the archaeological record, and what provides context to samples and artefacts is their sedimentary matrix (Butzer, 1980; Goldberg and Berna, 2010; Renfrew, 1976). Site-formation reconstruction through geoarchaeological analysis is thus vital to achieve the best possible knowledge of archaeological contexts and critical analysis of archaeological finds and time scales (Karkanas and Goldberg, 2018; Mallol and Mentzer, 2017). The knowledge about the Asturian Mesolithic geoarchaeological context is very limited, difficulted for over a century of research by its specific preservation conditions as carbonate-cemented deposits. In this work, we used a micromorphological approach to overcome that limitation

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and tackle the Asturian deposits formation through the study of two key-sites, El Alloru and El Mazo rockshelters. Through the scheme reproduced in Fig. 1, Vega del Sella aimed at explaining three fundamental aspects to contextualize the Asturian lithic industry that he meant to define: a) how the Asturian shell middens became carbonate-cemented, b) their chronological position between the Paleolithic and the Neolithic, and c) their functionality as waste disposal mounds. These three aspects will also be addressed in this paper on light of new geoarchaeological evidence.

In the 1910's through the 1930's, Vega del Sella also tackled the living areas of these hunter-gatherers. Both Vega del Sella and Hugo Obermaier, whose collaborations with the Count in Asturias grounded a substantial part of his work (Obermaier, 1916), believed that shell middens were but the disposal waste mounds and the corresponding living spaces were somewhere else, perhaps driven by the Paleolithic living features which they were used to find, with clear combustion features and fauna-processing deposits so abundant in the Cantabrian region's caves, but usually not found in the Holocene Hunter-Gatherers' layers. Dwelling features of prehistoric coastal foragers' remain a challenging and engaging issue for archaeologists given the evidence that human settlement in littoral regions is often associated with less mobility and diversified diet, and the consequences in social behaviour

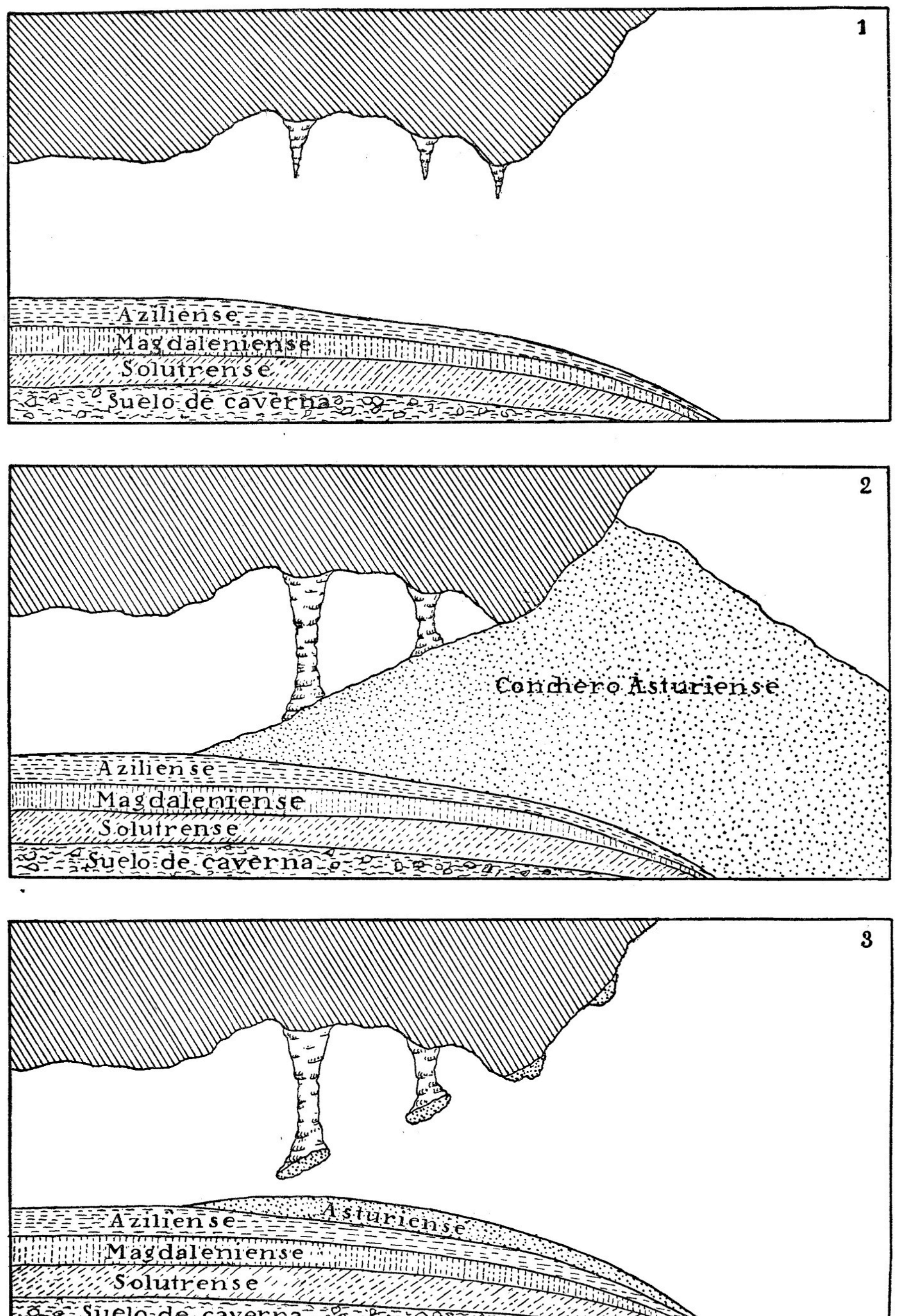

Fig. I.ª—Esquema representando el proceso del Asturiense en una cueva.
1, estado de una cueva a la terminación del paleolítico; 2, durante el Asturiense; 3, estado actual.

Fig. 1. Reproduction of Vega del Sella's (1923) Fig. 1 with schematic representation of the formation process of the Asturias shell middens. Legend transliteration: 1, state at the end of the Palaeolithic; 2, During the Asturian; 3, Present state.

towards higher level of sedentism (Arias Cabal, 2005; Arias, 2007; Straus, 2008). In this paper, we will also address this issue on light of what the formation processes reveal regarding occupation dynamics.

1.1. The Asturian record: state of the art of an archaeological paradigm

Defined as a macrolithic industry, 'Asturian' refers to the association between those tools made of quatzite pebbles, the most typical so-called Asturian pick (Fig. 2), with shell middens, which occurs in the littoral platform between the Cape Peñas and the Bay of Santander (~180 km), in modern regions of Asturias and Cantabria respectively, in the Spanish margin of the Bay of Biscay (Fig. 2). An outstanding concentration of sites is noted in the central part of this area, clustered in the municipalities of Ribadesella and Llanes, where Vega del Sella had his estate and worked more intensely. These deposits are dated between 8000 and 5000 BCE. Nearly all sites are shell middens (few exceptions consisting of isolated finds of Asturian picks), dominated by mollusc species living in the rocky intertidal (limpets [*Patella* sp], lined top shells [*Phorcus*

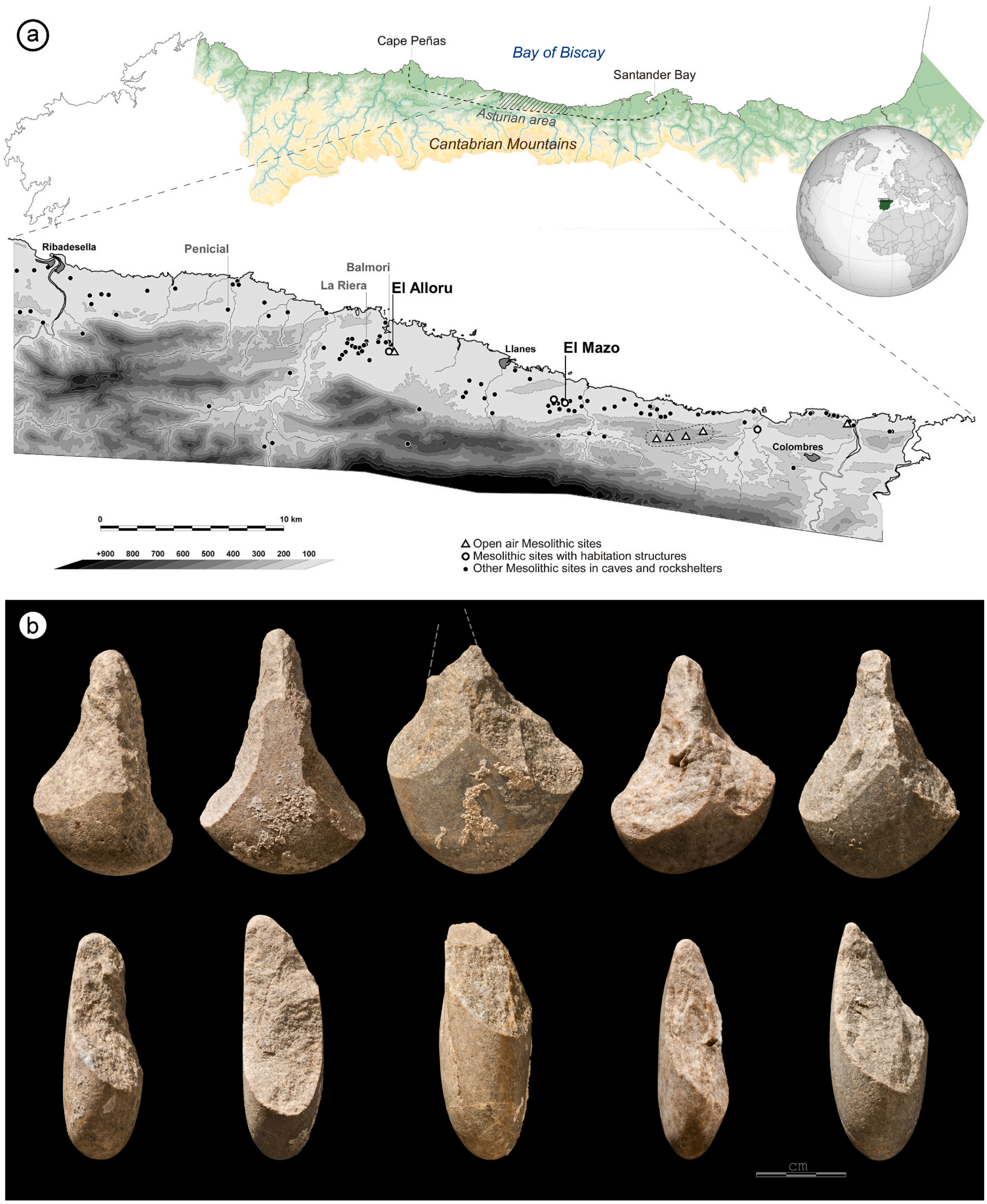

Fig. 2. Defining elements of the Asturian: a) location of the broad Asturian area in Western Europe (Earth globe credits: https://commons.wikimedia.org/wiki/File:Iberia_(orthographic_projection).svg; by Rob984, CC BY-SA 4.0 https://creativecommons.org/licenses/by-sa/4.0, via Wikimedia Commons; map of the Cantabrian region by L. Teira) and close-up in the core area of concentration of sites, with location of the sites under study (in black) and sites excavated by Vega del Sella mentioned ion the text (in grey) (map by L. Teira); b) Asturian picks recovered during the 2013 excavation of Unit 104 at El Alloru (photo by J. P. Ruas).

lineatus]), echinoids [*Paracentrotus lividus*], and crustaceans, among others; see (Álvarez-Fernández, 2015; Álvarez-Fernández et al., 2013; Arias et al., 2015; Gutiérrez-Zugasti, 2009; Gutiérrez-Zugasti et al., 2016). Abundant mammal bones, fishbones, and carbonized botanical remains have also been identified, while lithics, apart from typical Asturian tools, also include microliths (e.g. Arias et al., 2015; Gutiérrez-Zugasti et al., 2013). The record of human remains is fragmentary (Arias and Alvarez-Fernandez, 2004; Arias et al., 2007; Gonzalez Morales and Marquez Uria, 1978), although inhumations embedded in shelly deposits have been confirmed (Arias and Alvarez-Fernandez, 2004). We do not mean to be exhaustive in this brief contextualization, referring the reader to the work of Fano (2018) and references therein for recent syntheses regarding the different aspects of the Asturian record.

The Asturian is thus one of the often-cited Mesolithic 'cultures' of Atlantic Europe, where the exploitation of marine resources was central in the forager's lifeways, leading to the accumulation of large shell middens (Arias, 1999; Fano, 2018; Straus, 2008; Zilhao, 2000). Here lies the most significant aspect in our study, which is the preservation conditions of these deposits. The majority of Asturian shell middens are not conventional archaeological deposits within a stratigraphic framework that can be approached by traditional excavation methods. The typical Asturian shell middens are carbonate-cemented remnants, hanging from the karstic walls and ceilings of limestone rockshelters, or even smaller, often inaccessible karstic conducts, incredibly rich in archaeological remains, but disconnected from any other sedimentary deposits (Fig. 3).

Vega del Sella was deeply concerned in understanding the formation process of these shell middens, to contextualize the Asturian lithic industry he discovered, having excavated numerous cave sites (Vega del Sella, 1914, 1923, 1930). His work was so influential, that 'Asturian'

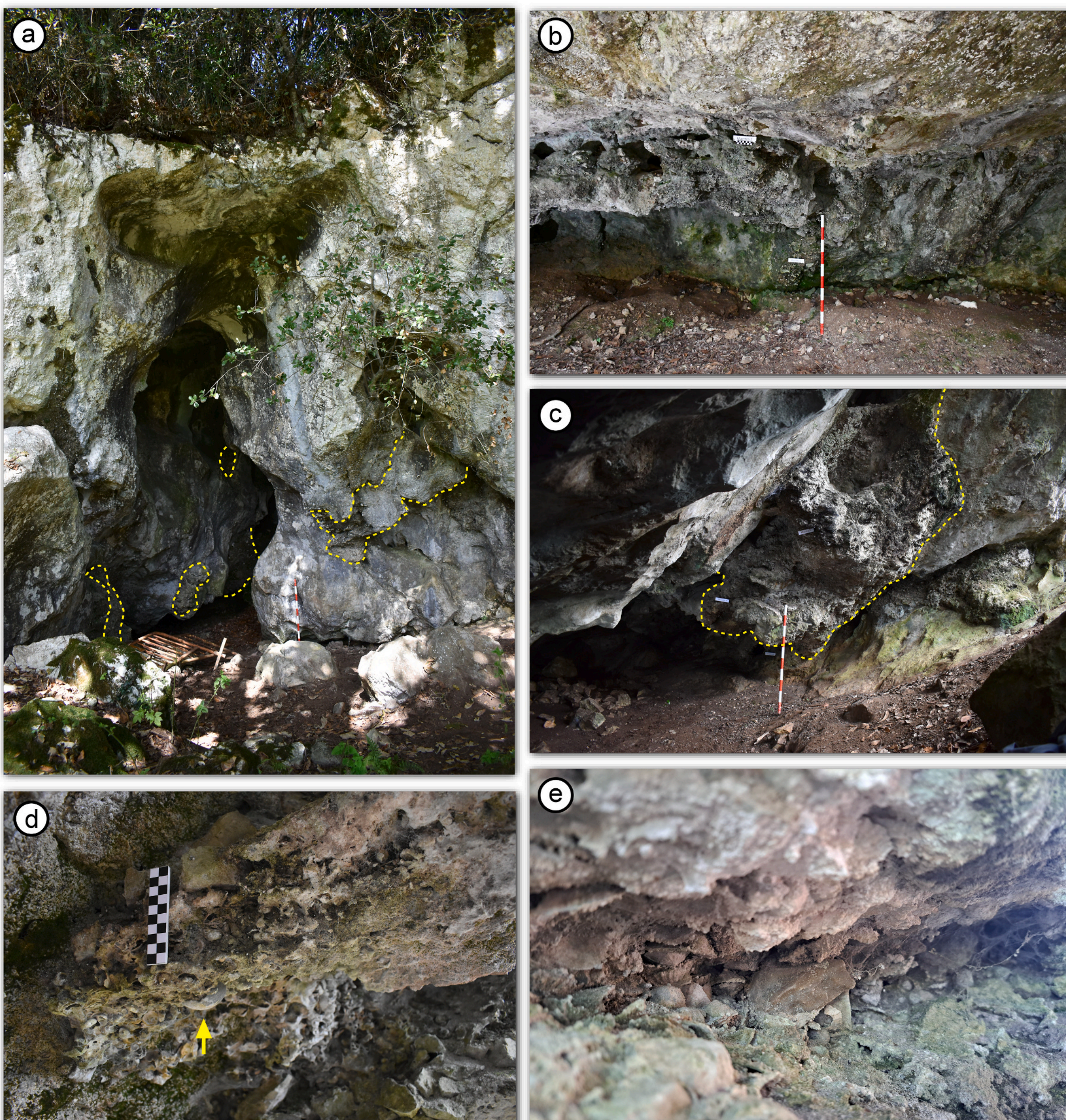

Fig. 3. Examples of typical Asturian shell middens: a) hanging patches of cemented remnants at the El Andriz rockshelter; scale bar = 1m (80 cm visible); b) hanging cornice from La Llosa rockshelter; scale bar = 1m; c) large, cemented remnants hanging from Fronfría cave; scale bar = 1m; note the taluses going down towards the inner karst in all these examples, with accumulation of rocks at the bottom; d) detail of cemented deposit at Peñavilla cave, where the abundance of mollusc shells and a knapped pebble (yellow arrow) adhered to the wall are visible (scale in cm); e) detail of another patch at Peñavilla adhered to a small ledge in the cave wall, showing mollusc shells with an Asturian pick in situ (see Fig. 2 for an approximate scale of the pick).

tools started being discovered throughout northern Iberia from Portugal to Catalonia through the first half of the 20th century, although without association with shell middens (Clark, 1976; González Morales, 1982; Serpa Pinto, 1928). According to the 1923 model (Fig. 1), the shell middens accumulated on top of previous Paleolithic occupations, as results of waste disposal by Holocene hunter-gatherers into the rock-shelters, filling completely the available space. Those parts of the deposits in contact with the wall became carbonate-cemented by water percolating through the cave walls like stalactites, while the bulk of the deposits disappeared by erosion after the definitive abandonment of the sites, remaining only the cemented parts adhered to walls and ceilings (Vega del Sella, 1923). This model has been uncritically assumed when interpreting the Mesolithic Asturian record, given that no alternative explanations have been proposed, and not unsurprisingly: such preservation conditions hampered the application of most traditional sedimentological techniques and archaeological excavation despite the long history of research.

In the 1950's the Holocene chronology was questioned by F. Jordá Cerdá and N. Llopis Lladó, who believed that the Asturian tools had to be older (Jordá, 1959; Llopis Lladó, 1953a, 1953b). They argued that the shell middens were accumulated in the Lower Palaeolithic filling the caves completely, before a phenomenon of karstic reactivation had washed out the shelly deposits, remaining only the cemented parts in the contact with the cave walls, similarly to what Vega del Sella defended. Afterwards, the Upper Paleolithic occupations took place, explaining the generalised absence of Mesolithic layers in stratigraphy superimposed to Paleolithic ones.

The early Paleolithic hypothesis found no support in the systematic palaeoecological studies carried out in the 1960-70's by G. A. Clark. The mid-Holocene chronology was established with the first radiocarbon dates of these contexts (Clark, 1976), while the first geoarchaeological studies of samples from cemented shell midden were carried out (Butzer and Bowman, 1976). The analysis consisted of macroscopic examination, grain-size analysis, pH and carbonate content. A microscopic examination of the sand fraction included a semi-quantitative estimation of roundness and wear of the grains. The samples are described as "semi-cemented", and after carbonates removal, the remaining sediment was a clayey loam, that the authors interpreted as colloidal precipitates, just as the carbonates. They furthermore note the absence of aeolian inputs, believing the angular quartz grains to be from bedrock alteration (Butzer and Bowman, 1976).

Overall, further geoarchaeological analysis of Asturian shell middens were avoided by sedimentologists working in the Pleistocene deposits of the same caves, as it is noticeable in later research at La Riera, among others (Hoyos Gómez, 1995; Laville, 1986; Straus et al., 1986). M. R. González Morales (1982) noticed that lack of detailed descriptions of the Asturian layers, highlighting that the "conditions for their formations are also discussible and with it their exact significance" (González Morales, 1982:64, free translation from the Spanish original).

Fano (2018) summarises the open questions about the formation of Asturian deposits in one: what dynamics generated these archaeological deposits? Micromorphological analysis have successfully identified naturally driven processes and human actions behind the accumulations of prehistoric shell middens in diverse environments worldwide (Aldeias and Bicho, 2016; Duarte et al., 2019; Kleijne and Huisman, 2023; McAdams et al., 2022; Villagran, 2014), therefore infer dynamics of human behaviour in the formation processes. In this paper we will test this method in carbonate cemented remains attached to karstic walls, but, unlike the cited studies, unattached from their original contexts.

2. Materials and methods

2.1. Geological setting

This paper focuses on the central Asturian area (municipality of Llanes, eastern Asturias, Spain), a narrow (5–7 km) littoral platform flanked by south by the Sierra del Cuera hills (ca. 1300 m high chain in the foothills of the Cantabrian Mountains) (Fig. 4) parallel to the coast, inducing a humid and temperate climate leading to well-developed vegetated soils and extensive deciduous woodland, highly contrasting with the drier Mediterranean conditions of Iberia south of the Mountains. The flattened littoral platform is deeply incised by the hydrographic systems draining to the Atlantic in the southern Bay of Biscay by torrential rivers running northwards.

The geological substrate consists of folded Carboniferous limestone, heavily affected by karstic processes, forming an intricate subterranean system, partially inundated by the sea (Hoyos and Herrero, 1989) (Fig. 4). The karstic modelling occurring since the Neogene formed a landscape of smooth, irregular heaps shaped by the evolution of abundant sinkholes, uvalas, blind valleys, and, naturally, numerous caves and rockshelters, many of which occupied by humans in the Paleolithic, notable by their outstanding accomplishments in cave art (Clark and Clark, 1975; Straus et al., 1986; Vega del Sella, 1930). The coastline itself is marked by abrasion platforms at the base of cliffs, dissected by rivers' mouths, where some beaches and small estuarine systems form. Soils in the littoral platform are generally thick, as they correspond to decalcification areas where insoluble sandy reddish clays accumulate, associated with sinkholes (Martínez García, 1981).

Some ten thousand years ago, the sea level started rising relatively fast from −27 m to up to −5 m at ca. seven thousand years ago, at a rate of 9–12 mm yr-1, when it slowed down until reaching its current position (Leorri et al., 2012). Index points reported by García-Artola et al. (2018) indicate that the sea-level was at *ca.* −10 m at 6000 BCE. This coastline retreat most certainly submerged Paleolithic sites as well as Asturian shell middens, noticeably in deposits that are nowadays exposed to wave action during the high tides (Fano, 2004; González Morales, 1982).

2.2. The case-studies

2.2.1. El Alloru rockshelter

El Alloru is a rockshelter in a small limestone outcrop surrounded by coalescent sinkholes filled with sandy-clayey materials, which surface is artificially flattened (Fig. 5). The main rockshelter is in the southwest face of the outcrop, at 25 m above the sea level. Smaller cavities exist along the outcrop border, some of them also with remnants of cemented shell middens. The main rockshelter is accessible by a slope downwards, and a ~50 cm thick shell midden is cemented over a small ledge in the backwall (Fig. 5), while a cornice of hanging remains extends along the shelter walls towards the exterior. This shell midden is known since Vega del Sella's (1923) prospections. In 2013 and 2017, interdisciplinary research carried out excavations at the site, digging two 2 m^2 test-pits, which location was guided by the results of previous geomagnetic survey off the site, to investigate possible Mesolithic living areas, which were confirmed and radiocarbon-dated to the early 7th millennium BCE (Arias et al., 2015, 2016). The Mesolithic occupation remains found in Test 1 (Supplementary Data 1) consisted of abundant mammal bones and charcoal along with few, very deteriorated marine shells and lithics in a dark brownish silty-loam matrix, in the interstices of limestone roofspall (Fig. 5). This layer presented slight internal differences, such as absence/presence of shells, variations in texture, that correspond to adjacent or partially overlapped Stratigraphic Units (Supplementary Data 1, Fig. 5). In the lower contact of the layer, two small negative structures carved in the underlying orange clay, filled with darker sediment, could correspond to postholes related to an open-air Mesolithic structure (Arias et al., 2015, 2016). A test pit of 1 m^2 (Test 3) in the downslope toward the interior of the rockshelter revealed only a sterile stony deposit with a clayey matrix overlying basal silty-clay deposit. In a dark sandy-clay pocket within the basal silty-clays, few limpets and topshells were recovered and radiocarbon dated also to the 7th millennium (Supplementary Data 1). The cemented shell midden inside the rockshelter exhibited an artificial semi-vertical

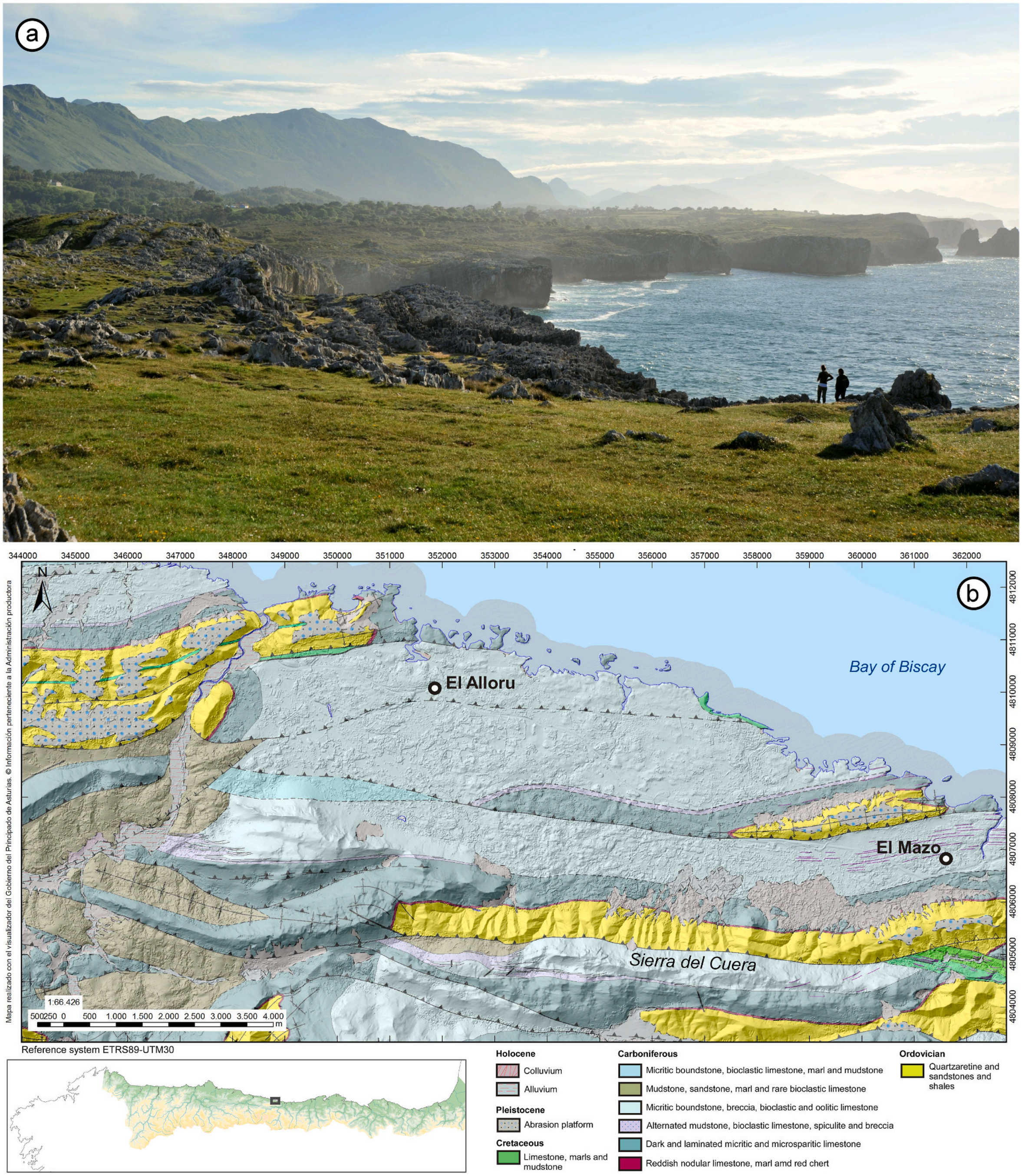

Fig. 4. Geological setting and location of case studies: a) general aspect of the littoral platform of eastern Asturias close to Llanes (photo by L. Teira); note the general flattened surface modeled by karstic processes and the Sierra del Cuera, part of the foothills of the Cantabrian Mountains, in the back; b) geological map (© *Gobierno del Principado de Asturias*) showing the location of the sites under study within the heavily karstified limestone perceptible by the surface shading.

face, probably result of early excavations, prior to Clark's (1976) visit, of which there is no record. The dating of shell samples from the shell midden revealed 6th millennium ages (Supplementary Data 1), indicating that the remains of occupation activities found in the exterior are older than those associated to the shell midden.

2.2.2. *El Mazo rockshelter*

El Mazo is a large rockshelter, 18 m long and 7 m deep, oriented to East, at 38 m above the sea level, overlooking a large collapsed sinkhole. The surface ground of the rockshelter describes a steep slope inward (Fig. 6), with an exiguous entrance to a small cave at the deepest point. Shell midden cemented patches cover the bottom of the wall (Fig. 6). Interdisciplinary research at the site has been ongoing since 2009 (Gutiérrez-Zugasti et al., 2013; Gutiérrez-Zugasti and González-Morales, 2014; Gutiérrez Zugasti et al., 2014). These works exposed a finely stratified Mesolithic shell midden to the North of the rockshelter, being one of the rare Asturian sites with non-cemented deposits, and the one with the most complex stratigraphy so far documented, with intricate shelly lenses and stratigraphic unconformities. This deposit was accumulated approximately between 7000 and 5500 BCE (García-Escárzaga et al., 2022). The complex history of site-formation processes of the shell midden was object of a comprehensive microstratigraphic study (Simões, 2019, also partially included in García-Escárzaga et al., 2022) that will be presented in a dedicated paper. For the present paper, only

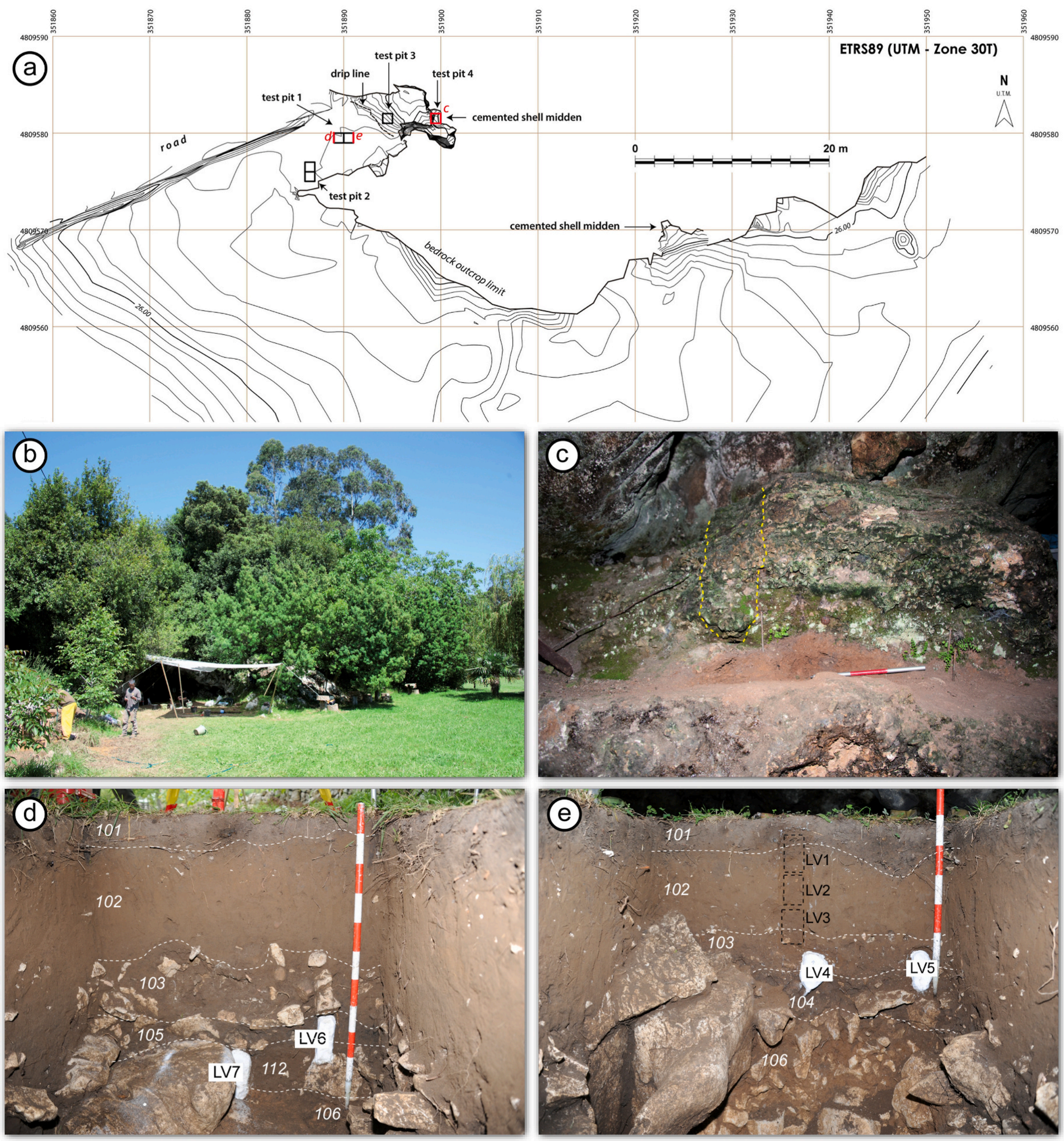

Fig. 5. El Alloru rockshelter: a) topographic plan of the site; the main rockshelter is located at the west side of the limestone outcrop; note the existence of other smaller shelters around it; b) view towards the main rockshelter, hidden by the vegetation in the back, showing the archaeological excavation in the open-air area; c) aspect of the cemented shell midden in the back of the rockshelter before sampling; the yellow dashed lines mark de limits of the extracted block for micromorphological analysis; d and e) west and east profiles, respectively, of Test 1, showing the stratigraphic units (white labels) and the micromorphological samples (black labels).

the cemented deposits will be addressed. It is though important to stress the existence of combustion features interstratified with shelly deposits in the excavated sector, suggestive of occupation activities on top of the shell heaps. There is no physical connection between the cemented remnants and the stratified deposit (Fig. 6).

2.3. *Archaeological micromorphology*

Micromorphology is the microscopic study of thin sections from artificially consolidated block samples, undisturbed and oriented, extracted from any archaeological sedimentary context, using principles of petrography (Courty et al., 1989). This technique allows us to observe the contextual arrangement cultural remains, at the microscopic scale, and their geometric and chronological relations with the surrounding sedimentary matrix, identifying aspects related to the formation and transformation of the materials (Nicosia and Stoops, 2017; Stoops et al., 2018). It is thus a fundamental technique to investigate the context of archaeological finds, particularly suited when the sedimentary deposits are the artefacts themselves (Miller, 2011; Shahack-Gross, 2017), such as shell middens (Aldeias and Bicho, 2016; Duarte et al., 2019).

The samples from the carbonate-cemented shell middens presented in this study were collected using an electric saw with circular blade for the initial incision and delimitation of the block, then completed with hammer and chisel. At El Alloru, one large block ~40 cm thick was extracted from the cemented deposit, taking advantage of a prominent corner representative of the whole deposit (Fig. 5). A second smaller block was retrieved adjacent to the first, inadvertently detached from the deposit during the extraction but considered suitable for analysis.

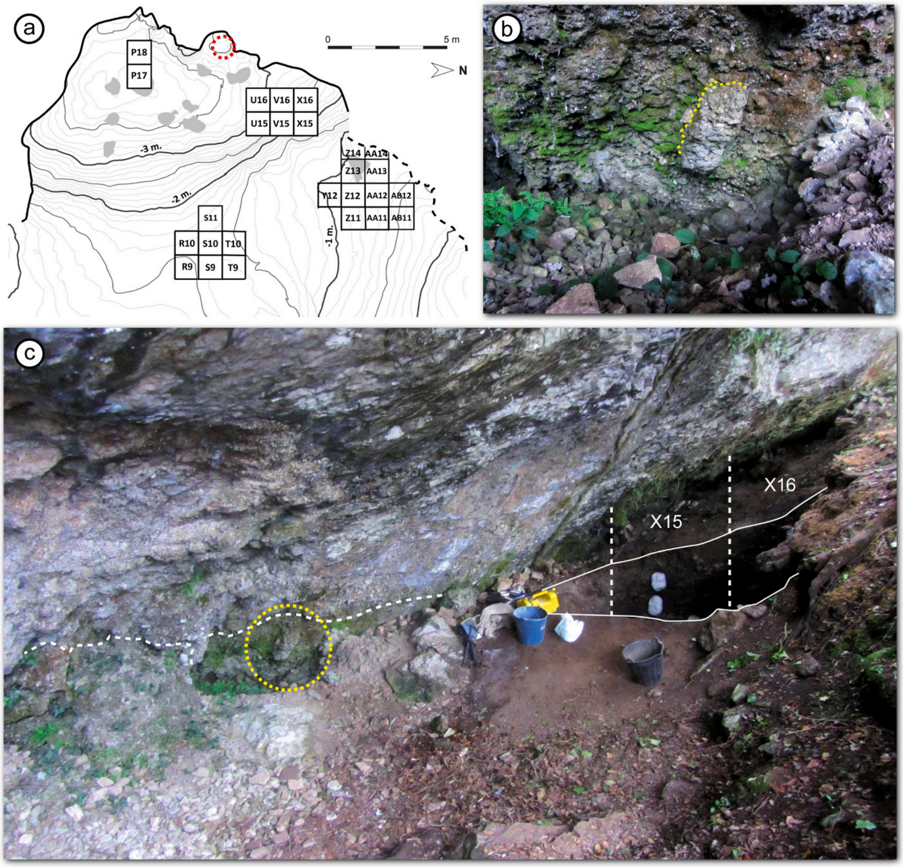

Fig. 6. El Mazo rockshelter: a) topographic plan with the excavation squares and a red dashed circle marking the location of the sampled block of cemented shell midden remnant; the stratified shell midden deposit, not cemented, is located in the X squares; b) view of the prominent cemented remnant extracted for micromorphological analysis delimited with yellow dashed line; c) view of the rockshelter towards the excavation area of the stratified shell midden with the squares in (a) indicated; note the location of the cemented cornice along the bottom of the limestone wall (top marked white dashed line), and the sampled block (yellow dashed circle).

The samples from Test 1 were extracted from the exposed profiles (Fig. 5), using a knife and trowel. All samples were encased in gypsum-plaster bandages to ensure its integrity during transport. At El Mazo, the cemented block was easily extracted with hammer and chisel given that it was a prominent hanging remnant (Fig. 6) with a suitable vertical shape representative of the deposit and wrapped in plastic and tape for transport.

All samples were unpacked and dried at ambient temperature in protected environment in a storage/field laboratory facility of the Instituto Internacional de Investigaciones Prehistoricas de Cantabria (Santander, Spain), where they were resin-impregnated by carefully drilling the plaster placing the blocks in containers that were filled with a solution of 7:3 polyester resin and styrene to which a 0.7 fraction of MEKP was added as catalyser, then allowing them to dry at ambient temperature for as much time as needed until fully consolidated. Once totally dried, the blocks were sliced into slabs at the DCITYM Laboratory (Universidad de Cantabria), from which a total of 14 thin sections were produced, at different laboratories, all with thickness of ~30 μm, normalised for petrographic analysis (Supplementary Data 2 and 3).

The micromorphological slabs and thin sections were digitized at 800 and 1200 ppp using a flatbed scanner for meso-scale observations (Arpin et al., 2002; Courty et al., 1989; Goldberg and Aldeias, 2016) and the petrographic study was carried out under plane and crossed polarized lights within a magnification range between 400x and 20x, while a polarizing stereoscopic microscope was used for lesser magnifications. The description of thin sections is based on the guidelines of Courty et al. (1989) and Stoops (2021) and systematized using an adapted table structure as recommended by Goldberg and Macphail (2006) and Macphail and Goldberg (2017).

2.3.1. *Carbonate microfabrics and microfacies*

Using micromorphology in archaeological contexts allows us to apply the concept of microfacies in its most original sense as it is used in sedimentology (Courty, 2001; Karkanas and Goldberg, 2018). Flügel (2004: 1), defined microfacies applicated to the petrographic study of carbonate rocks as "the total of all sedimentological and paleontological data which can be described and classified from thin sections, peels, polished slabs or rock samples." In this work, the carbonate microscopic structures cementing the shell middens, henceforth termed microfabrics, were identified according to Flügel (2004) and Pentecost (2005) terminologies.

The application of the microfacies concept in geoarchaeology reflects much of Flugel's definition adapted to the characteristics of repeated archaeological samples' stratification in thin section, aiming at synthesising deposits that share a set of specific microscopic attributes in thin section (Karkanas and Goldberg, 2018). The subsequent interpretation of those attributes, a combination of sedimentary components, their fabric, or other parameters, when consistently isolated from adjacent deposits, are interpreted as result of a certain process. The microfacies approach has revealed to be particularly suitable for shell midden contexts (Balbo et al., 2010; Villagran, 2014, 2018; Villagran et al., 2009). In the Mesolithic of the Iberia Peninsula, this approach allowed for the recognition of different types of deposits in primary and secondary positions, due to both natural and anthropogenic processes, as well as occupational surfaces and natural sedimentation during abandonment periods, within large open-air shell mounds (Aldeias and Bicho, 2016;

Duarte et al., 2019). A microfacies approach was applied to the study of the cemented shell middens, while at the exterior occupation of El Alloru, the concept was not considered operative due to the homogeneous character of the samples.

3. Results

3.1. El Alloru open-air occupation

The samples from the exterior deposit are composed of silty-clay matrix with a coarse fraction dominated by fine to medium sand composed essentially by quartz grains and larger limestone clasts (Fig. 7). Anthropogenic inclusions comprise chert fragments, charcoals and comminute bone fragments. Shells occur only in the Mesolithic Unit 104, and a single specimen is complete in thin section (*P. lineatus*), being most remains comminute fragments, all heavily weathered (Fig. 7). Biogenic components include fungal spores throughout the sequence and calcitic biospheroids in Unit 104 (Supplementary Data 4). In the Mesolithic units 104, 105 and 112, the matrix presents high amounts of charred organic matter. Unit 112 presents a microstructure in crudely bedded lenticular clayey pockets (Fig. 7) In terms of post-depositional processes, all carbonate materials (shells, biospheroids and limestone clasts) present advanced signs of dissolution (Fig. 7), although secondary carbonates precipitation is negligible. Soil formation indicated by

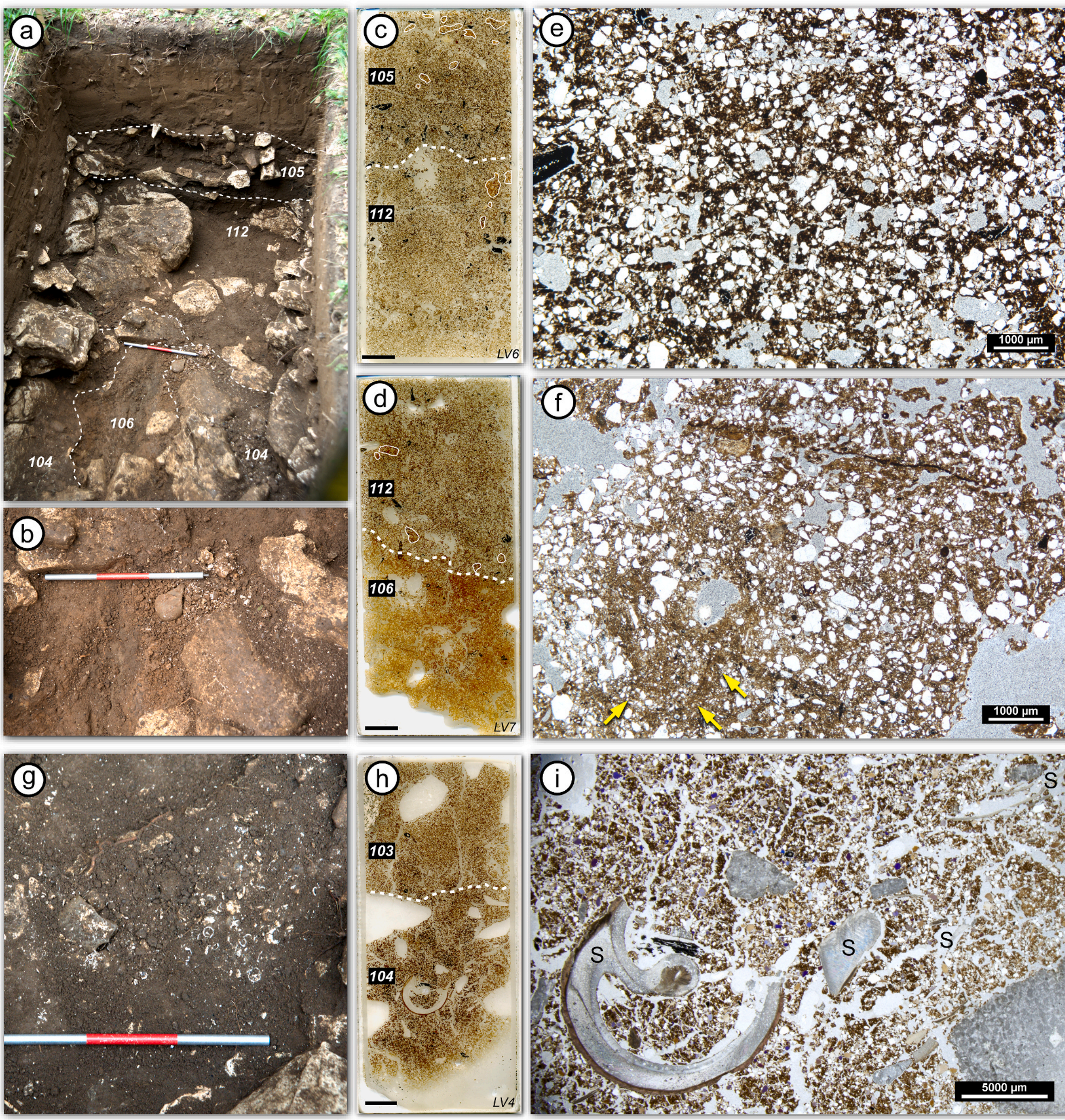

Fig. 7. Mesolithic layers in the exterior area of El Alloru: a) Test 1 excavation toward the West, showing unit 104 rich in shells in the interstices of the limestone blocks and the contact with unit 112, without shells, both overlying the orange clays of unit 106; unit 105 already removed and represented in the profile, overlying 112; b) detail of the contact between 104 and 106, with an Asturian pick visible next to the shells; c) and d) scans of the thin section LV6 and LV7 collected in the west profile; note the sharp contact between 106 and 112, the incorporation of aggregates from 106 (delimited by white lines) into upper sediments, the concentration of charcoals in 112 and 105 and large root channels in 105; e) photomicrograph of unit 112 showing crudely bedded lenticular pockets of sand and clay; PPL; f) microphotograph showing clay intercalations and convolution (yellow arrows) features, crude bedding of sand grains, and an organic pan, with polyconcave vughs and vesicles and shrinkage cracks; PPL; g) field photograph of the surface plan of Unit 104 with a concentration of scarce shells heavily weathered, next to an Asturian pick; h) scan of thin section LV4, in the contact between Units 103 and 104; note the pedality revealed by sub-angular peds; i) photomicrograph of unit 104 showing the scarce shells [S] and pedogenic blocky microstructure.

bioturbation and incipient blocky structure (Fig. 7).

The sterile basal deposit Unit 106 presents a massive microstructure and differentiated porosity patterns, with vesicles and closed vughs. The micromass exhibits clear striated b-fabric patterns and discrete but significant sedimentary structures, including crude bedding (Fig. 7), associated to horizontal clay intercalations and organic and iron-rich micropans (Fig. 7), while iron nodules are also abundant. Post-depositional processes include textural clay features, such as dusty, dark-brownish clay coatings on voids, well-oriented, normally not laminated, though a few laminated ones occur. These coatings contain organic and charred micro-particles finely mixed with the clay particles. The complete micromorphological descriptions of all layers can be found at Supplementary Data 4.

3.2. Shell middens composition

This section refers to both El Alloru and El Mazo samples, since most observations apply to both. When observed in micromorphological sliced slabs or in thin section at normal scale, the shell midden deposits appear like a chaotic jumble of very coarse components (intact shells, bones, pebbles, etc.), each one homogenously surrounded by thick and creamy carbonate coatings (Figs. 8 and 9), filling the packing voids. Many shells contain fine-grained sediment infills, which occur also as individual aggregates (Fig. 8). Following these observations, the constituents of the shell midden will be divided in three different categories: clastic components, fine-grained aggregates, and carbonate cement.

3.2.1. Clastic components

The shell midden's main components, welded together by the cement, are generally coarse pebbly in size, except those naturally smaller, such as echinoid spines. This group comprises single geogenic and biogenic items, including limestone pebbles, usually centimetric, mammal bones, shells of gastropods *Pattela* sp. (limpet) and *Phorcus* sp. (the lined top shell), echinoid *Paracentrotus lividus* (sea urchin) spines and tests fragments, calcareous seaweeds, and wood charcoal (Table 1, Fig. 9). Regarding the mollusc shells, almost all are complete (i.e., whole sections of shells), whereas fragments of shells are virtually absent. Small shell fragments appear only within silty-clay aggregates, usually burnt or calcined.

3.2.2. Fine-grained aggregates

The cemented shell midden contains sedimentary fine-grained aggregates of different compositions. Three types were identified: 1) carbonate mud, 2) combustion residues, and 3) pellets clusters (Fig. 10, Table 2). As said before, some shells filled with any of the fine-grained sediment are frequently observed in thin section. The fact that fine-grained sediment is preserved only in well delimited aggregates and sheltered micro-contexts provided by shells, suggests that these are reworked relicts of deposits formed elsewhere.

3.3. Carbonate microfabrics at El Alloru

The cement can be divided in two types: the stratigraphically older one, which is formed by micritic and microsparitic calcite, and a younger one, composed of larger, clear sparry calcite crystals growing on top of the former (Figs. 8d and 11). The older one presents characteristics of biogenic carbonates, composed by an array of complex microfabrics, from bacterial stromatolites to exuberant dendrites, thus

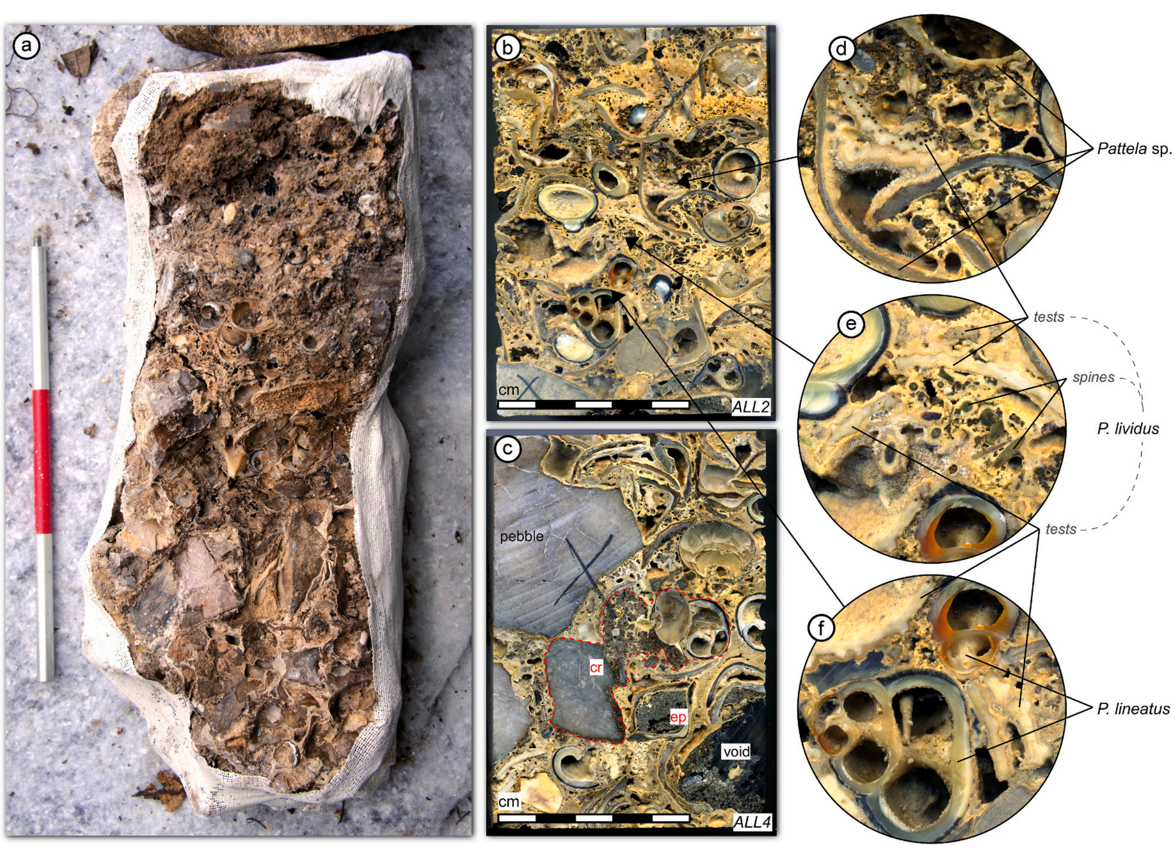

Fig. 8. Block sample of the cemented shell midden of El Alloru: a) aspect of the block after extraction from the cemented deposit; note the higher coarseness of components in the lower half than in the upper; scale bar = 30 cm; b) slab from the upper half; note the differential colour and porosity of the cement between the bottom and the top, and the chaotic distribution of components, the most abundant shown at 300% magnification in the outsets (d, e, f), where the different layers of carbonate cement evenly coating them can be observed; c) slab from to the lower half of the block sample; note the angularity of the limestone pebbles and the presence of fine grained aggregates: one aggregates of fine-grained combustion residues [cr], and excremental pellets [ep] infilling two limpet shells.

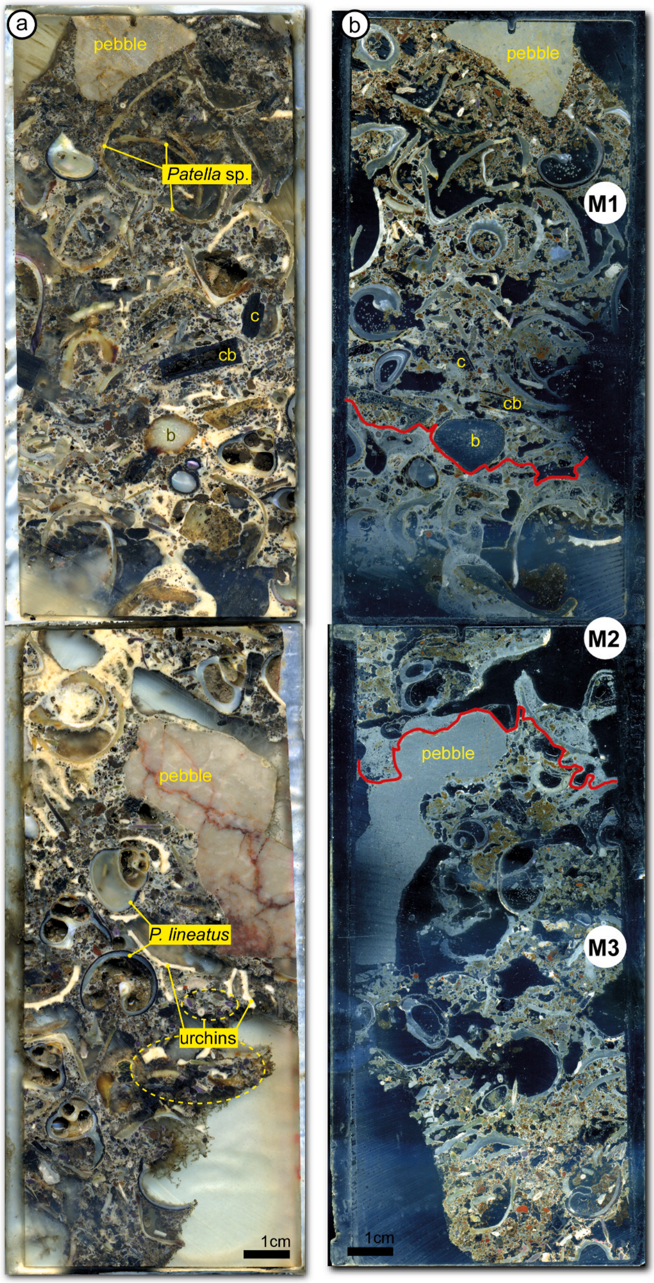

Fig. 9. Sample of the cemented shell midden remnant from El Mazo: a) scan view of the two slabs obtained after impregnation of the block, with annotation of some examples of gastropods and urchin elements, charcoal [c], bone [b], and carbonized bone [cb]; b) open scans of the thin sections mirroring the slabs in (a), with contacts (red lines) between the microfacies (circle labels); M2 corresponds to the areas in (a) where the cement is denser and brighter.

not being strictly a cement, but essentially calcareous tufa formations (Pedley, 1990, 2000) (Fig. 12). The superimposed younger cement appears chemically precipitated and should be regarded diagenetic, thus a true cement (Fig. 11).

Within the calcareous tufa facies there are crystalline microfabrics that can be associated directly with microbial action, i.e., carbonate crusts which calcification was mediated by microbes, such as cyanobacteria and green algae (Merz-Preiß, 2000; Pedley, 1992). Usually this is the case of the first generation of the cement in all samples and present great variability, from dense and massive micrite to crudely laminated, or microspar laminae. In some instances, these show distinctive colorations such as orange when enriched in iron oxides and dark/light grey

Table 1
Clastic components identified in thin section of the cemented shell middens of El Alloru and El Mazo.

Component	Description
Limestone pebbles	Coarse pebbles (up to 3.5 cm in thin section) in general angular and not spherical, of highly fossiliferous limestone from the local bedrock.
Marine gastropods shells	Complete specimens of *Patella* sp. and *Phorcus* sp. are dominant at the shell midden deposits. Fragments are extremely rare as clastic material and occur almost exclusively as components of fine-grained aggregates (Table 2).
Echinoids	Sea urchins *Paracentrotus lividus* have heavily calcified, globular to discoidal, hollow, endoskeletal tests that are composed of individual sutured, interlocking or imbricated calcite plates. Each plate behaves optically as a single, extensively perforated, calcite crystal and displays unit extinction. The sines have pores arranged with radial symmetry that in cross-sections, have a distinctive lobate or flower-like appearance (Scholle and Ulmer-Scholle, 2003). Echinoid shells at El Alloru shell midden are considerably large (up to 3 cm) test plates and both sites present abundant spines, neither with evidence of burning, except for those included in clayey aggregates (Table 2).
Bone	Most of the bones in the shell midden are considerably coarse fragments, in many cases up to several cm and very well preserved, without burning marks. Comminute fragments are rare as clastic material but may occur within aggregates (Table 2).
Charcoal	Overall rare, except in specific microfacies where it appears as coarse sand to gravel size pieces which woody cellular structure is moderately preserved. Finer pieces and dust charcoal is sometimes ca common components of clayey aggregates.
Calcareous seaweeds	Identified by their coaxial fine reticulate cellular internal structure that reflects the filamentous fabric of these organisms (Scholle and Ulmer-Scholle, 2003). Found as a common clast at El Mazo samples, but only as rare comminute fragments within fine-grained combustion residues aggregates at El Alloru.
Quartz silt and sand	Rare in general as clastic components, but present in some microfacies as overall angular quartz grains, in relative low amounts and scattered distribution.

Table 2
Fine-grained aggregate types identified at the cemented shell middens of El Alloru and El Mazo.

Aggregate type	Description	Origin
Carbonate mud	Dark- to greyish-brown, calcitic crystallitic clay with quartz silt (2%) and fine-medium quartz sand (10–15%), micritic nodules (5%), variable amount of tangled filamentous microfossils (10–40%) humified fine organic matter, and occasional phosphatic grains.	Biogenically precipitated (microbial, bacterial) deposits, possibly modified by reworking, anthropogenic activity and post-depositional processes.
Combustion residues	Greyish-brown clay, calcitic cristallitic b-fabric, with inclusions of micro-charcoal and charred organic tissues, dispersed ash pseudomorphs, burnt shells fragments, and rubified clayey aggregates as main components. Occasionally, foraminifers, filamentous microfossils, seaweeds (rodophyta) and phosphatic yellow, isotropic grains are also observed.	Reworked aggregates from anthropogenic burning and shellfish processing activities
Pellets	Clusters of pellety, granular microaggregates of greyish/ brown calcitic clay.	Insect/worms faecal pellets.

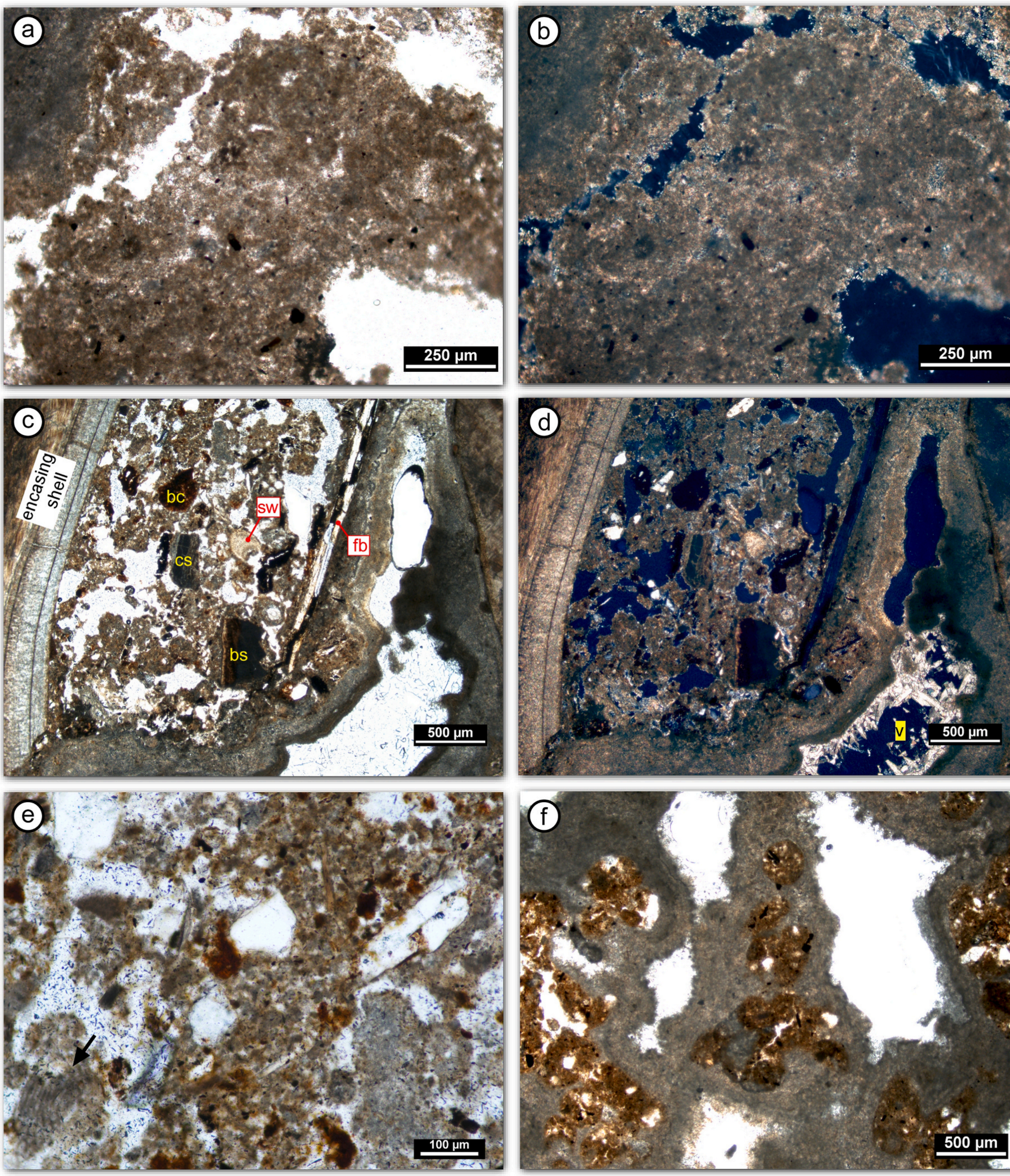

Fig. 10. Representative photomicrographs of the fine-grained aggregates identified in the cemented shell middens (all examples from El Alloru): a) and b) carbonate mud, mostly devoid of anthropogenic remains; PPL and XPL, respectively; c) and d) combustion residues infill of a complete limpet, with common inclusions annotated: burnt clay aggregates [bc], calcined [cs] and burnt [bs] shell fragments, bone, possibly fishbone [fb], and seaweed [sw]; note calcite enrichment of the micromass in (d), probably due to the presence of dispersed ashes; PPL and XPL, respectively; e) detail on combustion residues micromass showing dispersed ash rhombs and a fragment of ashed plant tissue (arrow), PPL; f) faecal pellets, PPL; from c) to f), the brownish-grey masses correspond to micritic cements, and the bright crystals in voids [v] visible in (d) to diagenetic calcite spar.

varying with the amount of organic matter. In calcareous tufas, this dynamic alternance in laminations following the clast surface' morphology is known to occur when there is frequent biofilm damage (Pedley, 2000), which must have characterised the initial moments of carbonate secretion in the shell midden deposit.

Superposed to the former, the coatings become more irregular, forming micro-stromatolites (laminated columns and domes), finger-like protuberances and finally peloids as the outermost fabric type (Figs. 11 and 12). Usually formed under more static water conditions, these characteristics strongly suggest the development of microbial mats. The filaments of these biological communities are protected by mucilaginous sheaths (when alive) which tend to precipitate carbonate in the form of micrite while its sticky surface traps and stabilises detrital carbonate mud, causing the irregularities in otherwise laminar growth surfaces (Ford and Pedley, 1996) (Fig. 12). Still within the tufa microfabrics, there are also abiotic crystalline structures, which formation relies on physico-chemical sparry precipitates (Figs. 11 and 12), rather than micritic (Pedley, 1992) that comprise essentially calcite morphologies such as closely packed fibrous crystals forming palisades, ray/fan crystals and dendritic morphologies forming feather-like crystals,

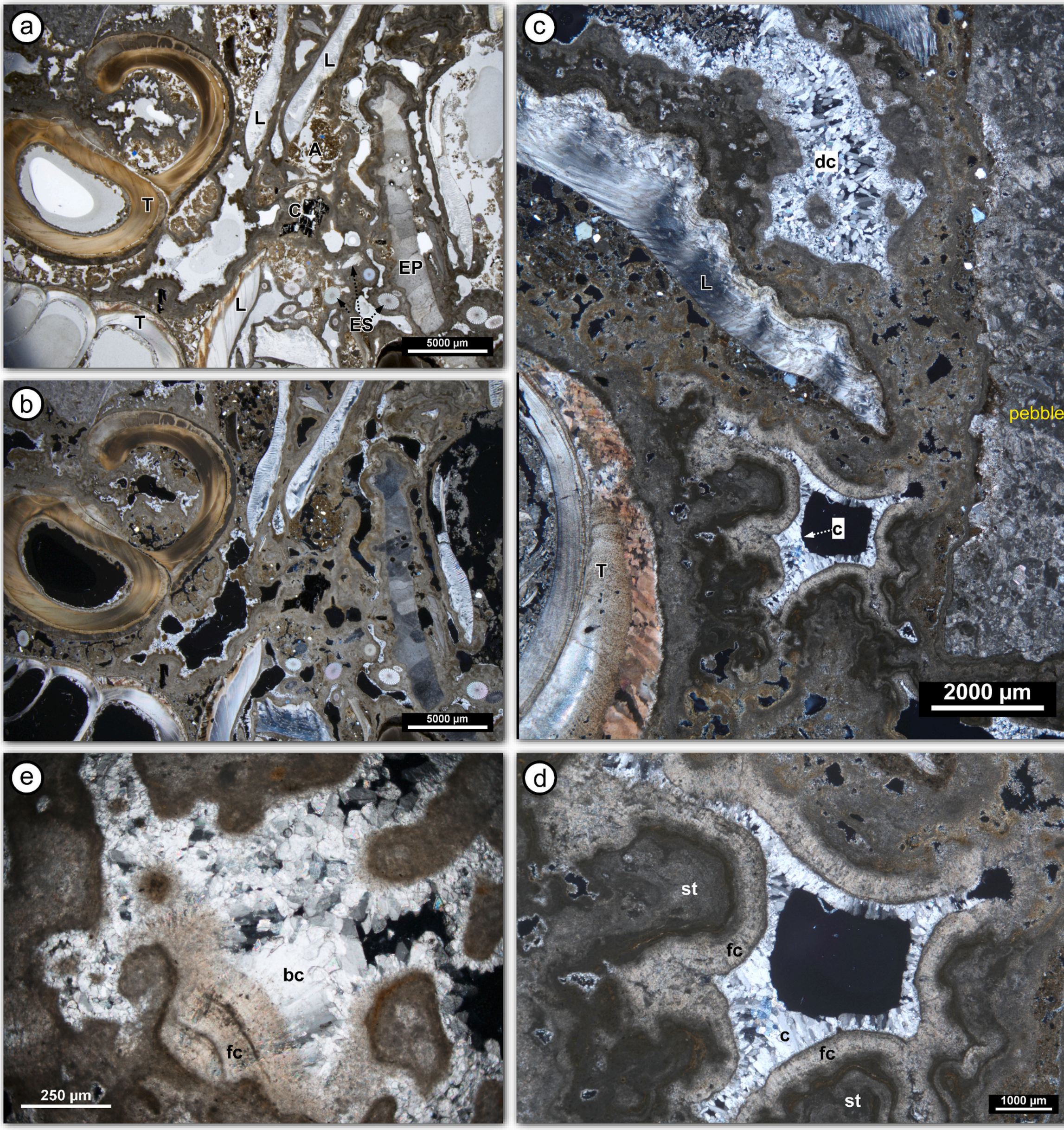

Fig. 11. General aspects of the cement microstratigraphy at El Alloru cemented shell midden in thin section ALL6: a and b) stereo-photomicrographs, in PPL and XPL, respectively; the cement coats each clastic component individually in incremental laminae progressively more irregular until merging components; the uppermost top shell presents brownish grey colours and spalling cracks likely due to heating; c) photomicrograph showing examples of sparry calcite infilling large voids, over the micritic cements (see Fig. 8d for a mesoscale example), the upper one completely filled with drusy calcite [dc] with pointy crystal terminations, and the lower one with calcite [c] crystals with blunted terminations due air trapped in the void; d) close-up of the lower void in c, showing an isopachous band of fibrous calcite [fc] between the micritic cement and the drusy calcite; note the stromatolitic microstructures [st] of the micritic cement; e) photomicrograph showing a syntaxial overgrowth cement of a botryoidal calcite [bc] crystal over superimposed rims of fibrous calcite [fc]; dogtooth calcite crystals grow around the micritic irregular growths; clastic components: echinoid test plates [EP] and spines [ES], top shells of *Phorcus* sp. [T], shell of limpets *Patella* sp. [L], charcoal [C], and fine-grained aggregates [A].

reflecting essentially varying waterflow regimes (Gandin and Capezzuoli, 2014) (Figs. 11 and 12).

The diagenetic cements, superimposed to the previous tufa facies correspond to later environmental modifications occurring soon after the biogenic carbonates have been deposited, originating clotted microfabrics (Pentecost, 2005). In Table 3, a list of all microfabrics identified in thin sections from El Alloru cemented shell midden, and used throughout the text, is provided, with interpretation concerning the forming environment of each one.

3.4. Microstratigraphy at El Alloru

The micromorphological analysis revealed that the distribution and amounts of the coarse components varied in superimposed layers. Adding to that, the carbonate cement microstratigraphy and post-depositional processes were also different through the same vertical sequence. Combining both observations (clastic components and cements' microstratigraphy), it was possible to categorise nine microfacies, with stratigraphic meaning concerning the formation processes of the shell midden, described in Table 4 and represented in Fig. 13, where it is possible to observe the stratigraphic framework in which the

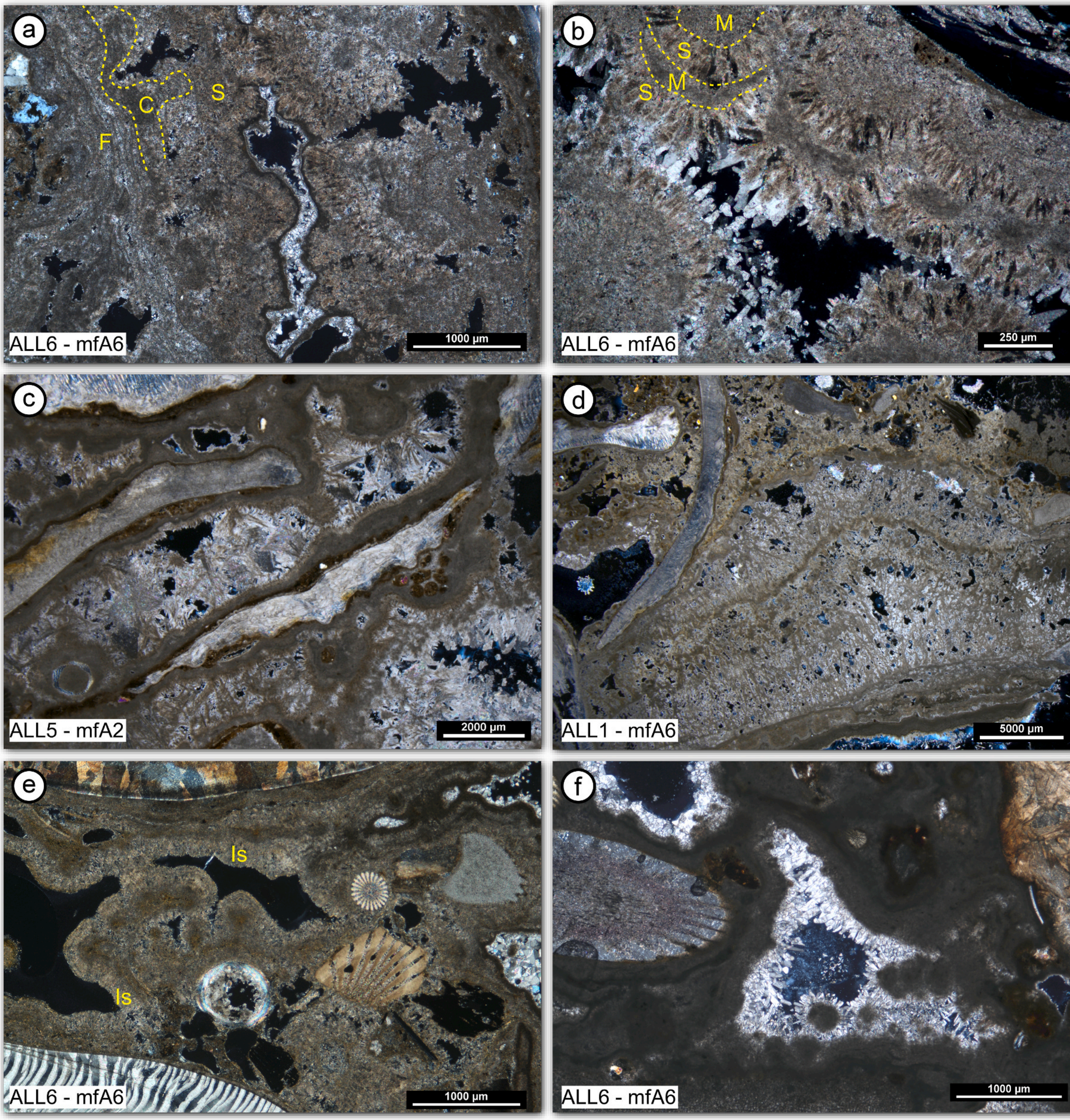

Fig. 12. General aspects of the calcareous tufa microfabrics at El Alloru, with sample and microfacies indicated: a) sequence of superposition of different microbial tufa-forming constructions, partially marked with dashed lines: calcified bacterial filaments [F], stromatolitic columns [C] and microsparitic shrubs [S], XPL; b) arborescent microalgal shrubs of cloudy spar crystals [S] alternated with micrite [M] layers; clear calcite spar overgrow the last event; XPL; c) examples of ray-crystals (lighter ones) growing over micritic substate around shell clasts; XPL; d) algal and bacterial control in the stick-like crystal arrangement and posterior cementation by microsparite; XPL; e) example of isopachous rim cements of fibrous calcite [Is]; XPL; f) isopachous rim of small bladed calcite crystals, most probably diagenetic, around very dense microbial micrite.

microfacies were identified.

3.5. Microstratigraphy at El Mazo cemented shell midden

The block of the cemented shell midden hanging from the ceiling of El Mazo rockshelter (Fig. 6) shows two layers that differ mainly in shell composition: the lower half (microfacies M3) consisting mainly of *Phorcus* sp. shells and echinoid test fragments, whereas the upper part (microfacies M1) is dominated by closely packed *Patella* sp. (Fig. 9, Table 5). Another common clast components are bone, charcoal, and calcareous seaweeds (Fig. 17). A major difference between the cemented shell midden and the non-cemented deposits at El Mazo is the widespread presence of small fragments of shells, mostly burnt (García-Escárzaga et al., 2022; Simões, 2019), which are completely absent from the former.

The carbonate microfabric of the cement consists of two basic types. The most striking one, occurring in both layers, is a generalised isopachous sparry crystals coating all clastic components and aggregates (Fig. 17). Calcite sparry crystals grew in the interstitial space between the clastic components creating closed vughs, with instances of both rough and smooth surfaces. Isopachous cements typically form in phreatic conditions (Flügel, 2004; James and Jones, 2016; Scholle and Ulmer-Scholle, 2003), and the smooth voids indicate that some air was trapped within some pores, preventing the complete growth of the calcite crystals (James and Jones, 2016). At some level stratigraphically placed in between the two layers, a different type of carbonate cement developed (mF M3), identified in thin section as well-developed dendritic crystals, considerably larger than sparry crystals, with stick-like ramifications and arranged in radiating fans (Fig. 17g), a calcite morphology that forms under rapid precipitation from fast-flowing,

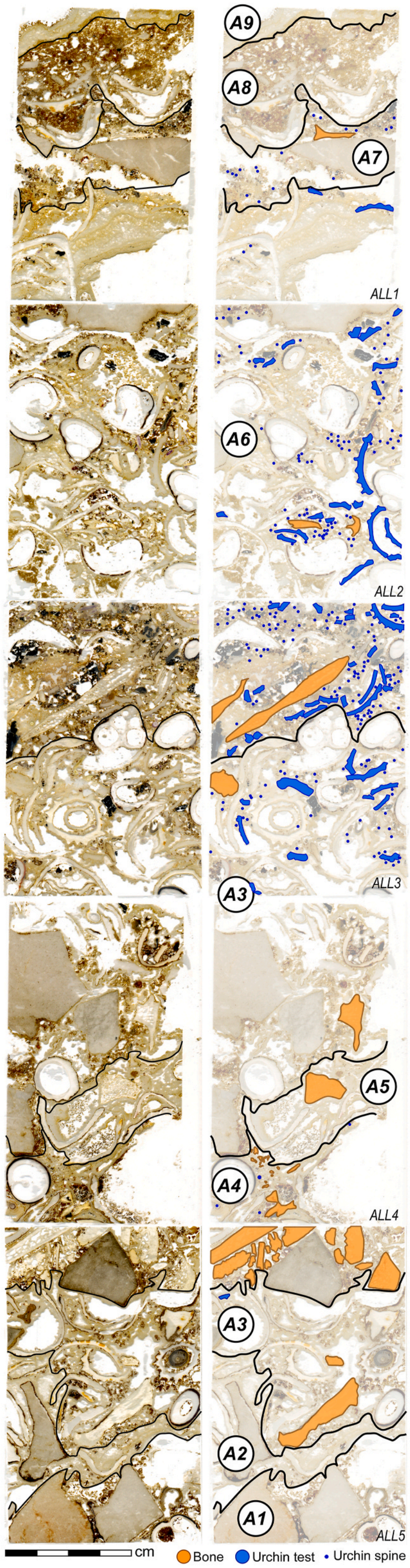

Fig. 13. Stratigraphy recognised in the cemented shell midden of El Alloru based on a microfacies (mF) approach: on the left, sequential scans of the thin sections obtained vertically through the block sample with mF contacts (black lines) and annotated scans of the same thin sections with mF names (circle labels), with indication of bone and sea urchin components as examples of differential vertical distribution of components.

supersaturated waters in spring systems (James and Jones, 2016). A last type of carbonate cement registered at El Mazo are needle fibre crystals (Fig. 17h), particularly frequent in the lower part (M2). Needle-fibre forms are thin (0.5–2 μm wide) and very long (up to 100 μm), randomly oriented crystals forming a meshwork pattern partially filling voids usually superimposed to previous cements, typically precipitated by fungal activity (Freytet and Verrecchia, 1998; Verrecchia and Verrecchia, 1994).

4. Discussion

4.1. Site formation processes

4.1.1. El Alloru: depositional history and occupation dynamics in the open-air area

The loamy groundmass must correspond to background sedimentary environment of karstic dissolution, whereas crude bedding suggests water lain deposition, while striated b-fabrics point to compaction and fabric rearrangements (Karkanas and Goldberg, 2018). The latter can be due to surface compaction under wet conditions, since micro-laminated layers of silty clay intercalated with sand and organic matter might also can reflect puddling in micro-depressions, that Rentzel et al. (2017) experiments suggest being caused by compaction, which prevent drainage. The same experiments on moist loamy sand soils also revealed the formation of polyconcave voids and crusts, both features observed in thin section of Unit 106 (Fig. 7f), as well as vesicles resulting from puddling (Deák et al., 2017). The main event of the rockshelter roof collapse also occurred during the accumulation of this deposit, contributing to compaction, but some hints point to human influence. The rare and comminute anthropogenic inputs (e.g., chert, bone, charcoal), together with the micromorphological observations above can be indicative of intense trampling on the surface, particularly in such high moisture environments (Rentzel et al., 2017). Accordingly, giving the overlying Mesolithic occupation debris and possible small negative structures carved on this unit's surface, human trampling might be one of the reasons of structural compaction of Unit 106.

The clay intercalations observed in Unit 106, associated with vesicles voids reflect slurry movements, a process usually associated with impure clay coatings (Macphail and Goldberg, 2017), which are common in Unit 106. The humified organic matter or iron micropans in clay intercalations can also be caused by trampling in wet surface (Macphail and Goldberg, 2017), while iron nodules (Fig. 7f) in different stages indicate a waterlogged environment (Macphail and Goldberg, 2017). Intense hunter-gatherer occupation over an unvegetated surface, periodically puddled, could also be in the origin of the dusty clay coatings, as result of percolation of charred organic matter and microcharcoal with rainfall water, after surface slaking when desiccated (French, 2003; Kemp et al., 2006; Macphail et al., 1987). Charcoal is possibly related with combustion activities carried out by the Mesolithic occupants, finely mixed in the sediments by trampling or transport in the flow, as suggested by clay invasion of the cellular structure (Deák et al., 2017). All the above, on the top centimetres from the upper contact of 106 indicate the impacts of mixed human occupations at a periodically wet surface, which was the main accumulation agent of the overlying layer, composed of Units 104, 107 and 112 (Supplementary Data 4).

The adjacent Units 112 and 104 differ by the concentration of shells in the latter, and the crude bedding in the former (Fig. 7e), suggesting a low energy water lain deposition. Their unconformable lower contacts with Unit 106 (Fig. 7d) indicate the new remarkably anthropogenic inputs of charred organic matter in the micromass, as well as coarse charcoal, bones, chert, and, in the case of constricted Unit 104, marine gastropod shells and lithics, including five picks that constitute the larger number of Asturian picks ever recovered from a stratified context (Figs. 2 and 7) (Arias et al., 2015). The scarce number of shells in this context might suggest localised and quick actions involving shellfish processing, or more random or ephemerous actions like dispersion by

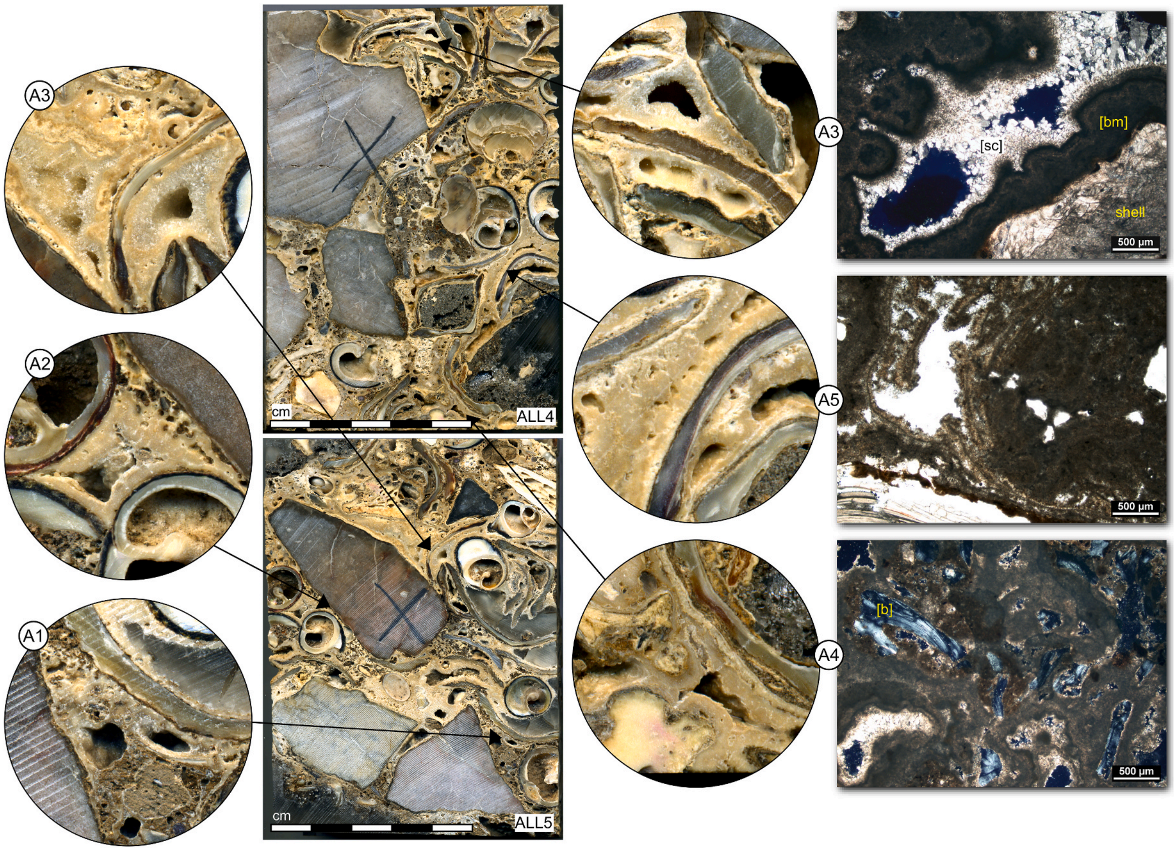

Fig. 14. – Carbonate microfabrics at the mesoscale in two slabs from the lower half of El Alloru block sample; microfacies indicated in circles (see Fig. 13 for microstratigraphic contacts); microphotographs in the right side show details of main features such as superimposition of diagenetic sparry calcite [sc] on biogenic micritic layers [bm] in mf A3 and the abundant bone fragments (larger example marked with [b]) cemented by biogenic micrite in mf A4, and calcified algal/bacterial filaments in mf A5.

trampling or localised discarding.

The abundant limestone clasts in this layer could likely have felt from the outcrop and been dispersed around by human trampling or site-maintenance-related activities. The advanced carbonate depletion in 104 is possibly associated with diagenesis (Fig. 7i), while bioturbation caused generalised homogenisation of the microstructure, indicating that this occupation surface suffered pedogenesis, thus was exposed for some time after abandonment, hence that this was indeed an open-air location. The channel and chamber porosity and blocky peds (Fig. 7h and i), abundant humified matter and worm's calcitic biospheroids, points to an exposed surface with occupation debris (shells) that went through pedogenesis after abandonment, developing an Ah-horizon. This palaeosoil was buried by the late Prehistory and Historic deposits forming the upper units (Supplementary Data 1 and 4).

4.1.2. El Alloru: depositional history of the cemented shell midden

The micromorphological analysis revealed that the cemented remnant of El Alloru is a stratified deposit, which is something entirely new in the Mesolithic Asturian record. As revealed by microfacies analysis, the clastic and fine-grained components refer to the original composition associated with the accumulation events of the different layers. The earlier stage of cementation of the different layers correspond to the tufa microfacies. Thus, biogenic carbonate precipitation was a background process happening during the shell middens' accumulation. Since tufa formation responds to different environments and forms microstratigraphic deposits directly dependent on those (Chafetz and Folk, 1984; Ford and Pedley, 1996; Pedley, 1990, 2000; Pentecost, 2005), it is possible to distinguish several environmental conditions between the depositional events, as represented in Fig. 13. As seen in section, the cement developed as coatings of regular thickness around each clast and aggregate, welding them together as the coatings progressively grow (Figs. 8, 14 and 16). The shape of carbonate coating is thus determined by the morphology of the substrate, i.e., clasts surfaces. This suggests that the clastic components were accumulated without any supporting matrix into tufa-forming environments, except for the very top layer of mF A8 (Figs. 13 and 17).

The observation of the sequence of block samples allows us to divide the whole deposit it in two parts approximately at the middle (Figs. 8 and 13): the lower half is coarser than the upper half, showing abundant centimetric pebbles and bones. This comprise microfacies A1 through A5 (Fig. 14). At the basal microfacies A1, carbonate mud aggregates are interpreted as result of reworking of an early carbonate-segregating environment (e.g., moss/lichen blankets) that was reworked together with pebbles and anthropogenic material that could have been tossed or rolled from earlier occupation areas nearby into an inundated area.

Microfacies A2 seems to be a tufa crust formed by well-developed dendrites and, microbial shrubs (Figs. 12c and 14), suggesting a hiatus in terms of accumulation of anthropogenic material for long enough to allow the development of different algal/microbial communities, which crystalline variability seems to respond to the establishment of fluctuating water table sporadically submerging the deposit, that went through different, perhaps seasonal, energy flows (Table 3).

In microfacies A3, the combustion residues, both shell-infills and aggregates (Fig. 8c), are most probably reworked, sourced from previously deposited anthropogenic sediments involving combustion activity. The clasts and aggregates were all equally affected by biofilm/microbial or algal colonisation over their surfaces (Fig. 14), which means that they were exposed to good lighting conditions (as the deposit is today) and

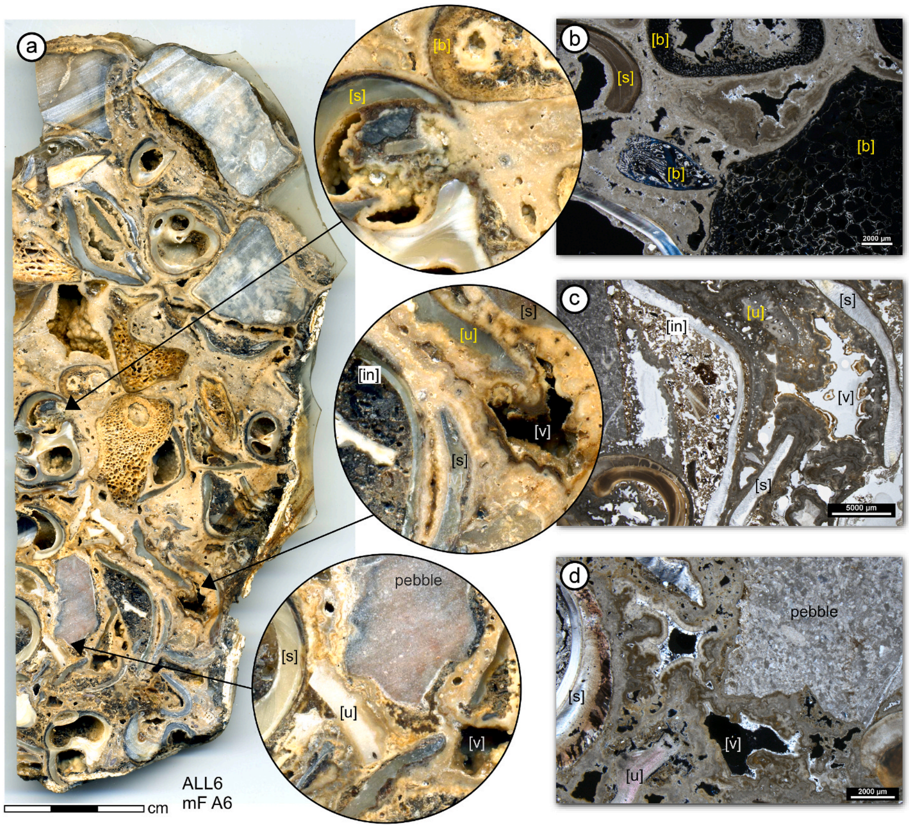

Fig. 15. Carbonate microfabrics at the mesoscale: a) the slab ALL6, in the middle of El Alloru block sample corresponding to mF A6 (see Fig. 13 for microstratigraphic contacts); stereoscopic images (b, c, d) represent the same area in thin section represented in the zooming in outsets next to them; b) microstromatolitic and shrubs carbonate microfabrics; c) fine-grain infill [in] of combustion residues inside a limpet shell and microlaminated microbial cements; d) diversity of micro-laminated cements; key for labels: [b] = bone, [s] = shell, [v] = void, [u] = sea urchin test.

possibly still water. This microfacies correspond to two layers in the stratigraphic sequence, one of them over 10 cm thick in thin section (Fig. 13), suggesting that it was accumulated at a regular, slow pace, so the microbial mats had conditions to form and calcify homogenously from the base to the top of the layer. In other words, this suggests that in this layer, anthropogenic inputs and the tufa-formation might be syn-depositional.

In microfacies A4 and A5, possibly very localised lenticular deposits intercalated within microfacies A3, the sorting of an anthropogenic components, respectively bones and limpets, suggests the influence of humans in their accumulation. The microbial mats that formed around the components calcify in particularly thick micritic coatings (Fig. 14), being algal filaments visible in A5 (Fig. 14), where the abundance of pellets suggests the presence of small invertebrates living in tufa depositional environments while active (Pentecost, 2005).

The upper part of the shell midden as represented in the block-sample corresponds mostly to microfacies A6 (Fig. 15), which has the largest variety of components, where the amount of echinoid parts stands out when compared to the previous layers (Fig. 13). The tufa microfabrics are also quite diverse, being the most striking the isopachous rims and fan/ray crystals associated to botryoidal crystals (Fig. 11), indicative of running water under considerable turbulence or supersaturation and supercooling (Chafetz and Folk, 1984; Gandin and Capezzuoli, 2014; James and Jones, 2016; Jones and Renaut, 2010; Pentecost, 2005). This is significant in this layer, being a thick accumulation of anthropogenic material, raising the possibility that such high-energy regime must have had some effect in the erosion and transport of the anthropogenic components. Thus, the accumulation of the material is arguably naturally driven rather than anthropogenically, although sourcing the components from previous anthropogenic deposits in the surroundings. At the top of microfacies A6, a thick (~1.5 cm) tufa crust formed as documented in thin section (Figs. 13 and 16), composed by several generations of superimposed crystalline dendrites intercalated by micritic layers, possibly reflecting alternating periods of well-developed bryophytes and microbial colonisation, thus varying flowing regimes.

Microfacies A7 is a thin deposit lacking coarse shells, being composed mostly by small fragments of shells and echinoids, contrarily to the previous microfacies where small shell fragments are virtually absent. A small amount of interstitial quartz sand and silt is present, being absent in other microfacies too. The above suggests that this thin layer is likely resulting from superficial reworking of debris from the surroundings. Abundant pellets clusters (Fig. 10f) suggest intense biological activity, directly related to invertebrates typically inhabiting tufa-forming environments (Pentecost, 2005). The clay coatings in the immediate part of the underlying microfacies A6 deposit (Fig. 16c) could hypothetically derive from eluviation of clay originally in microfacies A7 in a later stage of dripping water.

Microfacies A8, accumulated over microfacies A7, presents another exception in the shell midden where a clayey matrix prevails over carbonate cement, consisting of carbonate mud particularly rich in filamentous microfossils (Fig. 16). However, this microfacies also contains anthropogenic components such as *Pattela* sp. shells, bones, and few charcoals, embedded in the carbonate mud. The cementation of this microfacies (micrite and microspar hypocoatings) is more incipient than others, possibly because of the existence of a clayey matrix with massive microstructure. The last and top layer, microfacies 9, is a laminated tufa crust formed by successive microbial mats (Fig. 16), pointing to a last period of resurgence of the spring system but maybe in a protected situation propitious to the development of a horizontal microbial biofilm

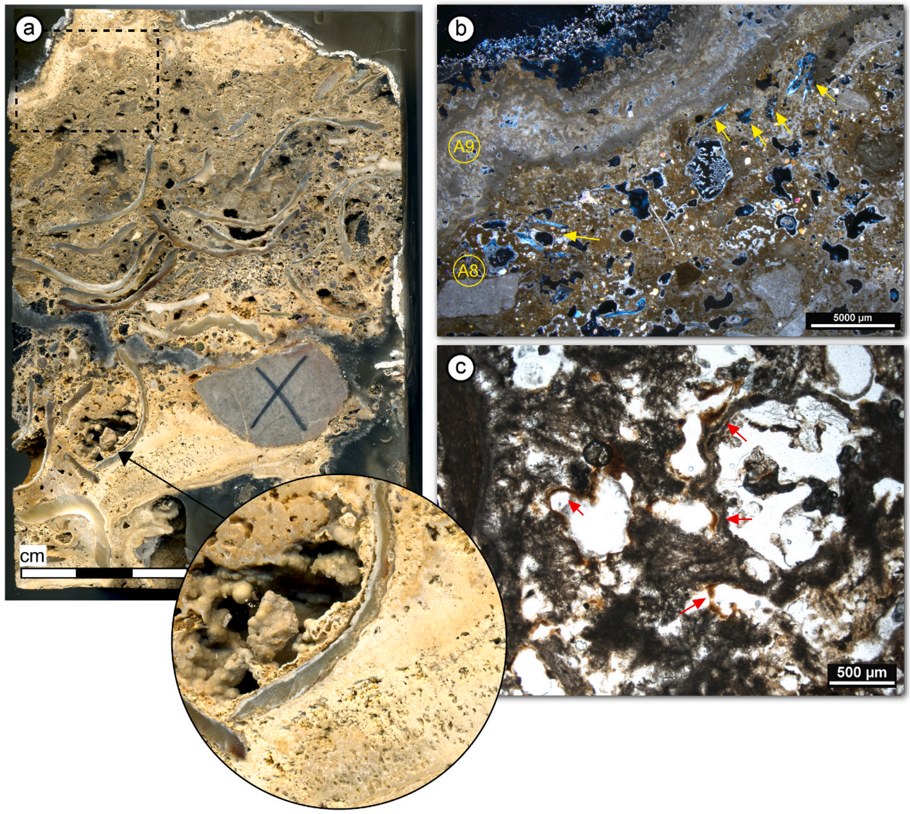

Fig. 16. Carbonate microfabrics at the mesoscale: a) the uppermost slab of El Alloru block sample (see Fig. 13 for microstratigraphic contacts); note the calcareous tufa typical microfabrics in the lower part, augmented in the outset, where examples of globular micro-domes and more porous calcified bryophytes branches, can be observed, versus the carbonate mud matrix of the upper part, corresponding to mF A8; b) stereoscopic image of the area in thin section corresponding to the dashed rectangle in (a), showing mF A8 with embedded bone fragments (yellow arrows) and A9, a capping layer of laminated tufa; c) aspect of dusty reddish clay coatings (red arrows) on the tufa crust on top of A6.

(Ford and Pedley, 1996).

4.1.3. El Alloru: diagenesis at the shell midden

A striking characteristic of the diagenetic cements is that they form isopachous rims. However, some variability is showed, sometimes even in neighbouring voids, in terms of the crystal morphology of the fringes, composed either by larger and pointy dogtooth calcite or finely packed bladed calcite (Figs. 11 and 12) (Table 3). These features reveal that the deposit was saturated with Ca-rich water, hence phreatic conditions prevailed (Flügel, 2004; Scholle and Ulmer-Scholle, 2003). The complete fillings of drusy calcite in some pores also points to phreatic environments, while few cases of flat crystals terminations (Fig. 11c) forming smooth surfaces point to the presence of air in the voids impeding the pyramid-like crystal point to form. This evidence suggests that probably the deposit was inundated by periodically high waters or perched water table. These features are particularly expressive in microfacies A3 and A6, where it certainly had implications on the configuration of the shell midden accumulation and arrangement of components. The rare cases drusy cements in form of meniscus point to vadose conditions (Flügel, 2004; James and Jones, 2016) and are concentrated in microfacies A7 in the upper part of the deposit, where the clay coatings possibly from dripping muddy water are also found. The differences in diagenetic cements being coincident with the layers' stratigraphical contacts suggest their formation in different phases, intercalated with different events of the shell midden accumulation dynamic, revealing that the cementation most likely occurred during the timespan of the Mesolithic occupations.

4.1.4. El Mazo: sedimentary and diagenetic dynamics of the cemented shell midden

At least two moments of shell debris accumulation, intercalated with three different moments of cementation, were documented (Fig. 9). Since the shells are anthropogenic, the differential sorting of species is likely reflecting pre-depositional human influence. However, the total excremental microstructure (Fig. 17c and d) points to high degree of reworking over at least two previous deposits resulting from distinct occupations or activities, explaining the difference in composition.

Phreatic conditions seem to have prevailed as revealed by the ubiquitous isopachous cementation in both layers (Fig. 17), through periodical water saturation from raising water tables. Clear gravitational signatures of vadose conditions such as pendants and meniscus are absent, pointing to a scenario like that of El Alloru: precipitation of calcite below the water table, in this case, however, without leading to more advanced stages of phreatic cementation, since there was no time for drusy calcite fillings, for instance. This also indicates that this area of the site was periodically inundated after each moment of deposition. Such conditions most certainly modified the primary geometric configuration and distribution of the archaeologic components. In between both layers, cemented by isopachous calcite coatings, there is a layer of crystalline tufa formed by large calcite dendrites (Figs. 9 and 17), which usually nucleate in fast-flowing waters characterised by high driving force (James and Jones, 2016), suggesting a higher-energy waterflow episode with plant growth between the two main depositional events.

4.2. Synthesis and outcomes of site formation analysis

The Asturian shell middens analysed revealed to be stratified deposits of anthropogenic components affected by calcareous tufa

Table 3
Carbonate microfabrics identified in the cemented shell middens.

Carbonate microfabrics	Description	Origin
Micritic coatings (Figs. 11 and 12)	Massive to laminated micritic crusts, with mouldic pores sometimes filled with microspar. May develop spongy (micro-thrombolitic) microfabrics and peloids, usually cemented by drusy calcite or isopachous dogtooth calcite (see below). Occasionally form domes and micro-stromatolites. Calcified cyanobacterial filaments are sometimes visible	Biogenic Calcification of microbial/algal mats typical of shallow water environments (Flügel, 2004; Gandin and Capezzuoli, 2014; Pedley, 2000; Pentecost, 2005)
Shrubs (Fig. 12a and b)	Formed by two distinct fabrics: 1) laminae of cloudy spar crystals organised in fan-like, radiating chains that corresponds to calcified bacterial clumps, developing arborescent structures, sometimes with a layer of clear micrite intercalated between layers of spar, and 2) intricate micritic and spar rhombs organised in a dendritic fabric.	Biogenic Calcification of bacterial colonies, reported from very shallow pools and sheets of still water and hypersaturated water flowing on sub-vertical surfaces of very shallow slow-running watercourses or micro-terraces (Gandin and Capezzuoli, 2014). The micritic layers intercalated with the radiating spar crystals have been interpreted as reduced carbonate precipitation during colder seasons (Chafetz and Folk, 1984). Other observations suggested that the shrubs (radiating spar) develop when the water flow level drops after evaporation, whereas the mud (micrite) is deposited during flooding periods (Gandin and Capezzuoli, 2014).
Fibrous crystals (Fig. 12e)	Closely packed finely fibrous crystals with sweeping extinction under XPL, almost as if it was a single crystal. They form crusts ca. 200–500 μm thick with regular banding. These structures occur isolated and arranged in undulating fringes, forming palisades coating cavities. Occasionally include botryoidal features.	Biogenic These crystals grow normal to the substrate and parallel to the direction of flowing water forming laminar bands, whereas botryoids form in less steep surfaces. Appear to be related to hypersaturation of turbulent waters as a consequence of vaporization and rapid CO2 degassing induced by the fast running, high-flux regime (Gandin and Capezzuoli, 2014). Banded fibrous crystals in travertines have been reported in hypogean phreatic environments within vent conduits (Gandin and Capezzuoli, 2014).
Dendritic crystals (Fig. 12c and d)	Feather/plume-like crystals or more complex, irregular branching, generally from a central, long crystal, resembling a stick, forming crusts up to 1 cm thick, with micritic clots and lenses intercalated. At El Alloru seems to correspond to algal bushes, since the crystal growth seem to be controlled by the algal filaments (Pentecost, 2005), with fan-like structures composed of long crystals radiating from a single point in the substrate upon which they develop. In hand sample these are readily identifiable in thin section at 1:1 scale.	Biogenic Feather-like crystalline crusts precipitate from thin sheet of running water on irregularly steep surfaces (Gandin and Capezzuoli, 2014), being a common crystal morphology in tufa deposits related to cascades (Chafetz and Folk, 1984; Pentecost, 2005)
Isopachous cements (Fig. 12e and f)	Isopachous cement appear in thin section as regular rims around cavities and grains (particularly peloids) formed by dogtooth and bladed calcite crystals. Dogtooth is a type clear calcite crystals up to hundreds of micrometres long, with uniform extinction, characterised by sharply pointed, sometimes blunted, terminations (Flügel, 2004). Bladed calcite rims have more regular thickness and are composed by smaller and elongated crystals (Flügel, 2004; Scholle and Ulmer-Scholle, 2003).	Chemogenic Isopachous rims of chemogenic calcite crystals are typical of marine cements, but also meteoric phreatic environments (Flügel, 2004; James and Jones, 2016).
Drusy cements (SI Fig. 11c–e)	A void-filling cement composed of equant to elongated clear sparite crystals with uniform extinction, which size increase towards the centre of the void, creating a mosaic pattern. At El Alloru forms thick linings in irregular surfaces on earlier cements, many times filling voids completely.	Chemogenic A common meteoric cement (Flügel, 2004). In phreatic conditions, the pores were completely filled with water, the drusy crystals will have pyramidal terminations. Under vadose conditions (water/air interface) the crystals have smooth termination, caused by the air trapped in the cavity (James and Jones, 2016)

development, separated by periods of stasis, during which diagenetic cementation occurred. That is new outcome number one. The cemented shell middens encase micromorphological evidence linked to anthropogenic contexts derived from combustion features, composed by charred and calcined residues of plants, shells, clay, and seaweeds, in a matrix composed of ash (Fig. 10). No Mesolithic combustion features were identified at El Alloru open-air site, but this evidence from the cemented shell midden seems clear regarding their past existence somewhere else in the rockshelter or very nearby. The occurrence of combustion residues infilling shells (Fig. 15a–c) also indicates that such primary contexts, be it combustion features or residue dumps, were indeed rich in shells already before their accumulation in the current cemented deposit. This inference is supported by that exact circumstance being documented at El Mazo non-cemented shell midden deposit.

This scenario suggests that the locations of these primary shelly deposits at El Alloru were in the proximity of the current position of the cemented remnants. Furthermore, the syn-depositional tufa development reveals that, once deposited, these components were affected by calcareous tufa growth. The carbonate cements observed in thin section resemble the petrographic character of those forming in spring settings (Chafetz and Folk, 1984; Flügel, 2004; James and Jones, 2016; Jones and Renaut, 2010; Scholle and Ulmer-Scholle, 2003). That is new outcome number two. Such dynamic hydrological activity, with fluctuating water tables and varying energy regimes hints the possibility of spring waters being an active reworking agent of previously deposited anthropogenic components. However, some instances of item selection within microfacies (e.g., bones [microfacies A4], or shells of a single species [microfacies A5]) are more parsimoniously explain as human induced. This could result from episodic direct tossing of items after a

Table 4
Microfacies (mF) identified at El Alloru shell midden, from the oldest to the youngest (bottom to top).

mF	Clastic and fine-grained components* and porosity	Carbonate cement microstratigraphy (older to younger)
A1 (Fig. 14)	Interconnected pebbles and Phorcus sp. shells Carbonate mud aggregates 40% void space	Tufa microfabrics: 1) Very thin and irregular microbial mats, usually not layered and developing domes 2) Few and weakly develop shrubs and fan/ray crystals Diagenetic microfabrics: 3) Dogtooth fringes and drusy ca lcite pore fillings
A2 (Fig. 14)	Large pebble (x1), few interconnected Pattela sp. shells Few pellets 10% void space	Tufa microfabrics: 1) Very thin (>1 mm) micro-layered pendants around pebbles 2) Thin microbial mats evolving to small stromatolitic columns and peloids. 3) Shrubs of dendritic micrite and spar rhombs. 4) Fan/ray fibrous crystals 5) Abundant large dendritic crystals (fan like). Diagenetic microfabrics: 6) Drusy fillings, rare and very localised.
A3 (Fig. 14)	Interconnecetd Pattela sp. shells, bones, charcoals, small pebbles, echinoid spines Combustion residues adhered to and trapped between limpets Pellets 25% void space	Tufa microfabrics: 1) Microbial mats evolving to small stromatolitic columns and small peloids with clotted microfabric Diagenetic microfabrics: 2) Isopachous rims of bladed calcite to uneven dogtooth arround clasts, peloids and pores' walls, with pointed terminations 3) Drusy fillings with pointed terminations
A4 (Fig. 14)	Interceonnected large bone fragments, comminute bone, pebbles, Pattela sp and Phorcus sp. shells, echinoids Scarce combustion residues 30% void space	Tufa microfabrics: 1) Dense and laminated microbial mats, almost completely filling the inter-clast pore, forming fenestral voids Diagenetic microfabrics: 4) Fine to very coarse dogtooth crystals rims around clasts, peloids and pores' walls 5) Drusy pore fillings
A5 (Fig. 14)	Interconnected Pattela sp. shells, bone (x1) Pellets infilling shells 40% void space	Tufa microfabrics: 1) Thick and irregular dense microbial mats with large networks of calcified algal filaments 2) Weakly developed microspar and micritic fringes
A6 (Fig. 15)	Echinoid spines and tests, Pattela sp. and Phorcus sp. shells, charcoals, bones, pebbles Combustion residues, carbonate mud 30–40% void space	Tufa microfabrics: 1) Thick dense microbial mats, massive to laminated, sometimes developing stromatolitic structures and peloids, and locally calcified filamentous cyanobacteria are visible. In thi mF, the laminated manicrobial mats have some laminae composed of impure clay poorly oriented, with calcitic crystallitic to undifferentiated b-fabric, exhibiting gravitational geometries, e.g., hanging from stromatolitic structures. 2) Abundant fibrous crystals in fan/ray fabrics, isopachous rims and banded palisades, all more or less combined with micritic layers. 3) Abundant dendritic crystals, algal bushes and dendritic shrubs, forming crusts up to 1 cm. thick at the top of the mF, with micritic clots and layers intercalated. Diagenetic microfabrics: 4) Localised sparry cements (dogtooth and drusy) usually in closed voids associated to fibrous fringes. 5) Dogtooth and bladed calcite rims around dendritic crystals of 4). 6) Discrete alveolar septal fabrics. Other post-depositional features: - Reddish clay coatings
A7 (Fig. 16)	Bones, shells, echinoids, charcoal, pebble (x1), sand and silt Granular combustion residues, pellets 10% void space	Tufa microfabrics: 1) Non-laminated thin microbial mats with micro-spar rims Diagenetic microfabrics: 2) Few and localised meniscus-like drusy cements Other post-depositional features: - Reddish clay coatings in the contact with underlying mF6
A8 (Fig. 16)	Matrix composed of carbonate mud with *Pattela* sp. shells imbricated at the bottom, charcoal, bones, comminute bone, calcareous seaweed, silt and sand 10%void space	Tufa microfabrics: 1) Incipient microbial mats forming some peloids Diagenetic microfabrics: 2) Microspar coatings 3) Rare drusy fillings
A9 (Fig. 16)	None	Tufa deposit, with typical fenestral prosity at mesoscale, formed by different layers of growth. 1) Microbial mat with visible calcified filaments, cemented by microspar rims 2) Microbial mats forming layeres micrite with finger-like and stromatolitic structures 3) Cloudy, massive micrite Other post-depositional features: - Impure reddish and poorly oriented clay coatings

*By decreasing order of relative abundance

Table 5
Microfacies (mF) identified at El Mazo cemented shell midden.

mF	Clastic and fine-grained components* and porosity	Carbonate microfabric
M1	Interconnected *Pattela* sp. shells and bones, few *Phorcus* sp. shells and echinoids, calcareous seaweeds Abundant pellets, spongy aggregates of carbonate mud and combustion residues 10% void space	1) Isopachous dogtooth sparry calcite
M2	Interconnected *Pattela* sp. shells and bones, few *Phorcus* sp. shells and echinoids Abundant pellets, spongy aggregates of carbonate mud and combustion residues 10% void space	1) Layered, large dendritic calcite crystals in radiating fans ("algal bushes")
M3	Scattered *Phorcus* sp. shells and echinoid tests, broken *Pattella* sp. shells, small bones, charcoal, calcareous seaweeds Abundant pellets, spongy aggregates of carbonate mud and combustion residues 40% void space	1) Isopachous dogtooth sparry calcite 2) Needle fibre calcite

*By decreasing order of abundance

specific processing activity while a spring was active, probably in rather calm regimes, as evinced from the earlier microfabrics of tufa formation. Higher energy events during raising water levels could have been particularly active in reworking previous deposits, for instance as recorded in microfacies A6 at El Alloru and M2 at El Mazo, during which, by hypothesis, the rockshelter could be unoccupied, but the deposits from previous occupations were exposed to spring flooding. Overall, it seems that the current deposits results from combination of accumulation promoted by rolling or intentional tossing of specific items during occupations, and natural reworking of previous deposits that could be anywhere in the rockshelter. In this scenario, the chronological inversion revealed in the sequentially radiocarbon dated shell samples from El Alloru (Supplementary Data 1) makes sense.

Eventually the cementing deposits were completely saturated in calcium-rich water, either by water table rise or perched water tables. That is new outcome number three. One must admit that mid-Holocene rainfall regimes allowed for such high water-table and saturation level of these karstic systems, since nowadays most Asturian cavities, just like El Alloru and El Mazo, function as sinks instead, and curiously enough, do not exhibit any substantial signs of continuous spring activity, such as tufa formations (except the shell middens). However, closer to the present sea-level, we do find sheltered limestone outcrops with springs at ground level next to a liveable platform. This is exemplified in Fig. 18, displaying a spring in a rockshelter, without visible Asturian remains, in November 2022, located near the mouth of the river valley running towards the current beach of Cuevas del Mar, where Asturian shell middens in the caves on the cliffside are exposed to sea waves. This could illustrate exactly what we envision for Asturian in the Early-Mid Holocene. Paleoenvironmental data points to a maximum increase in precipitation in the Cantabrian region during that period, with speleothem exponential growth starting overall around *ca.* 7500 BCE, along with documented rising water levels in mountain lakes, to which the Cantabrian glaciers melting could have contributed considerably (Morellón et al., 2018). On light of this, it seems reasonable to hypothesize that water table levels could be indeed higher, or perched, at an altitude enough to saturate the karstic systems more inland in the littoral platform, where Asturian hunter-gatherers were moving.

Increasing effects of seasonality in the Holocene (Morellón et al., 2018) might be linked to the varying hydrological energy inferred from carbonate microfacies in the studied Asturian shell middens. These variations appear to have occurred both in energy and water table level, as recorded in examples of differential micro-layering of the tufa facies. In the meanwhile, probably also influenced by the pace of successive intermittent occupations of the sites, anthropogenic materials were being reworked into the subaerial environment of the slurry, microbially colonised tufa-forming environments of active karstic springs. The Mesolithic hunter-gatherers could thus occupy the rockshelters mainly when conditions were dryer, but most probably always with fresh water available. In wetter seasons, the external areas of sites such as El Alloru would be puddled and not suitable for occupation. Isotopic data from shell incremental carbonate layers from Asturian shell middens indicate that marine gastropods were exploited year-round (Bailey and Craighead, 2003; García-Escárzaga, 2020). The Asturian littoral platform provided the Mesolithic hunter-gatherers the opportunity for occupying rockshelters in a dynamic moving system throughout a dense network of karstic massifs at many different elevations with independent hydrological systems.

Mesolithic hunter-gatherer episodic occupations during dryer seasonal periods within a tufa-forming environment have been recorded at the Artusia Rockshelter in the upper Ebro basin in the foothills of the Pyrenees (northern Spain), although in a fluvial context (García-Martínez de Lagrán et al., 2016). Intact combustion events were documented alternating within a sequence of aggradational tufa deposits, suggesting a high frequency of alternance between the occupations and the waterflow variations. Further micromorphological evidence of hunter-gatherers periodically living in rockshelter near carbonate springs comes from the Pleistocene site of Obi-Rakhmat, in Uzbekistan (Mallol et al., 2009), where the anthropogenic materials were found to have been reworked during periods of no-occupation, by spring waters. Like at these two examples, at the Asturian shell middens the identification of internal stratification, provided by compositional and microstructural differences observed in thin section, testifies that these processes did not happen at once, but intercalating periods of accumulation and tufa-formation, perhaps controlled by the phreatic level fluctuations.

In sum, the site-formation analysis allowed us to establish three new things for the Asturian contexts: 1) that Asturian shell middens are stratified deposits and bear evidence of combustion features within shelly contexts, in secondary position, 2) that the primary cementing material consist of calcareous tufa likely formed by spring activity, and 3) that phreatic conditions prevailed during the cementation of the deposits. The new outcomes contradict three a priori expectations from Vega del Sella's pioneer model of Asturian shell midden site-formation, as it is shown in Table 6. Let us go through how each one fits the existent model of Asturian formation processes.

4.3. Building upon the 1923 model

4.3.1. Activity areas vs waste mounds

First, the primary accumulation of the deposits is assumed by Vega del Sella to result directly from waste disposal by hunter-gatherer living on the open areas adjacent to the rockshelters (Arias et al., 2015; Vega del Sella, 1923). This hypothesis has been both validated and refuted, as opposing evidence has appeared in research carried out since then. The sites of El Mazo and El Toral III also yielded hearths and a presumed posthole, respectively, on shell midden layers (Gutiérrez-Zugasti et al., 2013; Noval, 2007). Contrarily, there is the evidence from the open-air occupation area in front of El Alloru rockshelter analysed in this article. Therefore, the current evidence offers divergent possibilities for the function of the shell middens and the location of living areas. It is however interesting that the occupation floor documented in Mazaculos II (González Morales, 1982; Gonzalez Morales and Marquez Uria, 1978) is at the base of the deposit, corresponding to the first occupation, that was later buried by successive shell midden deposits, all adjacent to the rockshelters's wall. There might be a parallel for a similar situation at El Alloru, with the open-air surface being older than the cemented shell midden, which is the possible past existence of shelly deposits over the

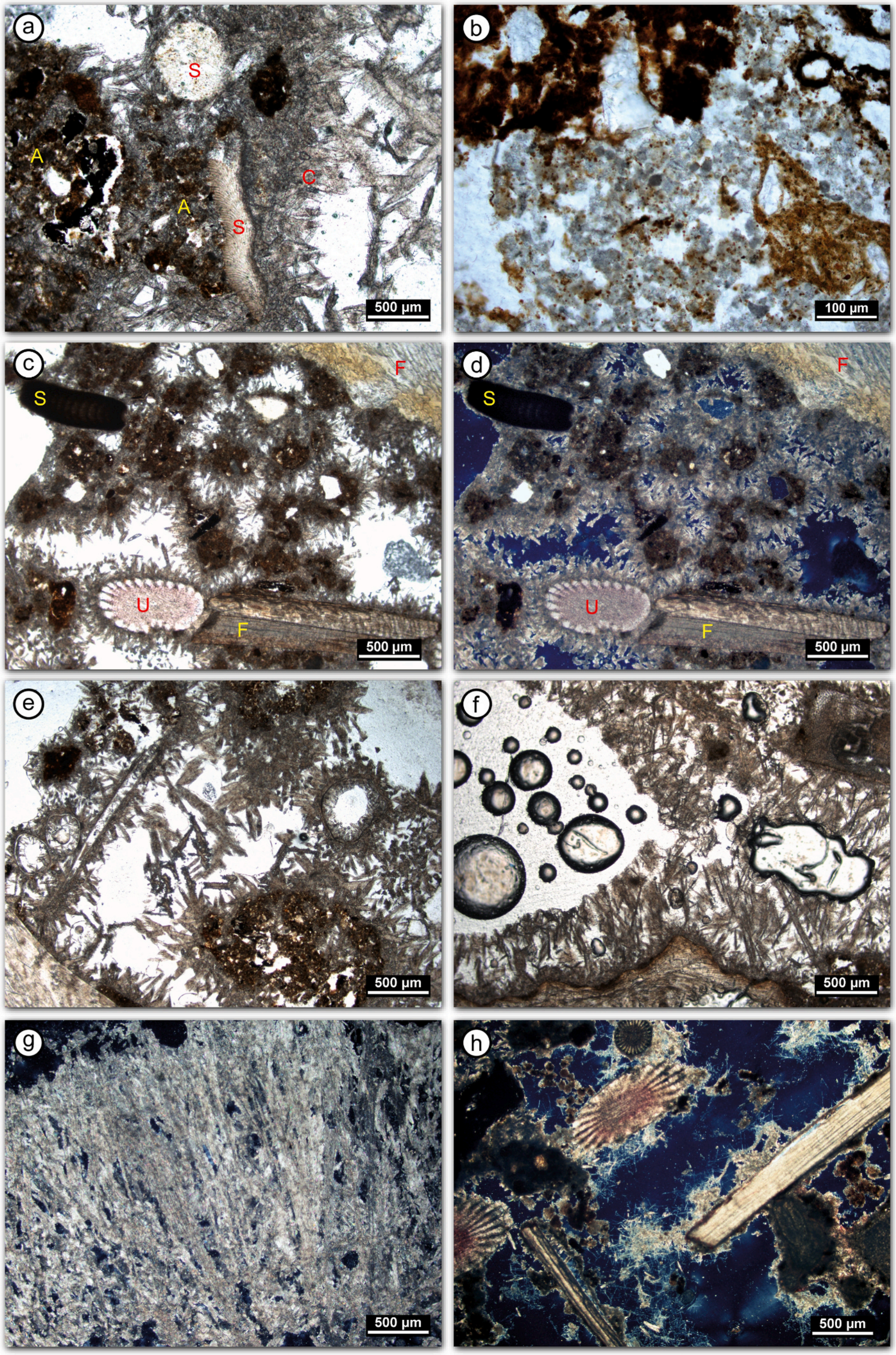

Fig. 17. Components and carbonate cements at El Mazo: a) examples of two calcareous seaweed particles [S] and combustion residues aggregates [A] cemented by sparry calcite [C]; PPL; b) close-up of a combustion residue aggregate where well-preserved ash rhombs are visible; PPL; c and d) excrement pellets, dominant in the micromass of the cemented shell midden of El Mazo, where seaweed [S], urchin spine [U] and shell fragments [F] are also visible; note the isopachous rims of sparry calcite; PPL and XPL, respectively; e) cementation by sparry calcite crystalls overgrowing around shells of probably microscopic crustaceans living in the tufa forming environment; PPL; f and g) two different examples of thick crusts of dendritic calcite from microfacies C2; PPL and XPL, respectively; h) cementation by mesh of needle fibre calcite in the lower part of the block; XPL.

open-air occupation surface that were eroded, with the difference that in this case the occupations were documented so far only away from the limestone walls. Such deposits might have had combustion features, explaining the presence of such remains in secondary position in the cemented deposit.

From the micromorphological analysis of El Alloru and El Mazo cemented remnants it seems that shells were a major component of the anthropogenic deposits resulting from occupation activities, and that those involved intense combustion, thus it is likely that such features were in adjacent areas of both rockshelters and were entirely reworked. Thus, the Asturian cemented deposits cannot be regarded as direct waste dumps, since they are intensely reworked and in secondary position, which does not allow us to infer what the last human action that produced them was. Even microfacies A4 and A5 at El Alloru are not context-secured enough, thus we prefer to conservatively consider that those microfacies with single-type items, even if human-selected, are intensely reworked by spring activity, since the location of the human activity that generated them would not be the place where the shell

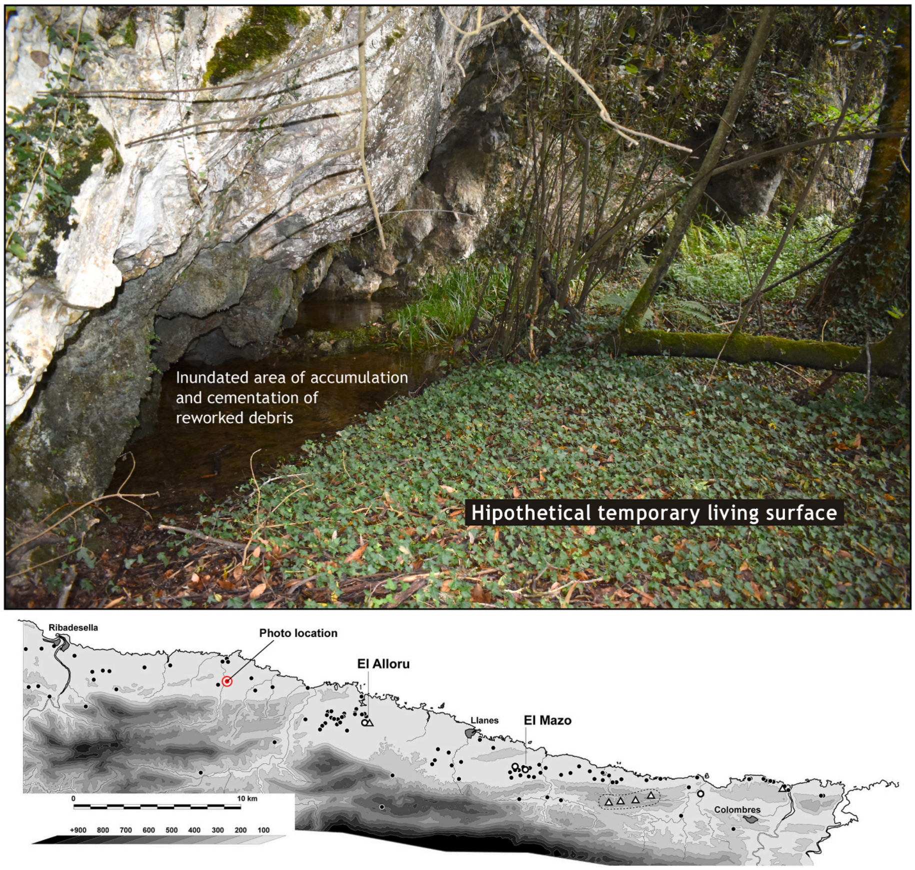

Fig. 18. Rockshelter with active spring in November 2022.

Table 6
Expectations from Vega del Sella (1923) *versus* geoarchaeological evidence.

Feature	1923 model assumptions	Expected features	Geoarchaeological evidence (this paper)	Interpretation
Carbonate cement	Mainly from dripping water	Gravitational features (e.g. pendants)	Isopachous cements, microbial mats, drusy calcite	Mainly from tufa
Watertable	Mainly vadose conditions			Mainly phreatic conditions
Timing of cementation	One event after definitive abandonment (postdepositional)	Homogenous carbonate microfacies	Different carbonate microfacies stratigraphically separated	Several events of cementation during/ between occupations
Stratigraphy	Paleolithic deposits below the Asturian	Existence of a slope towards the outside of the cavities	Most cavities exhibit taluses inward	Most Asturian deposits have no connection with other not cemented, stratified deposits.

midden is today. For all the above, it seems erroneous to envisage the cemented shell middens as what is left from past anthropogenic continuous mounds resulting from regular waste disposal into rockshelters.

4.3.2. *Cementing process*

The second outcome, that the primary cementing agent is linked to spring activity that furthermore seems to be syn-depositional, does not agree with Vega del Sella's premise that the cementation of the hanging remnants is caused by water coming from above, because in that case, the expected cement forms would be speleothems chemically precipitated, instead of springs' calcareous tufa. Calcareous tufa derives from living bacterial, algal or bryophyte plant communities associated with small invertebrate fauna that need sunlight and air, thus need to be on exposed surfaces and, specifically in some microfacies at El Alloru, periodically submerged.

Another significant aspect is that cementation by dripping water from above would have generated gravitational cements, like micro-speleothems and meniscus (Flügel, 2004), which are virtually absent. The chemogenic cements corresponding to the last phase of each cementation cycle are phreatic, which is the third outcome, opposing the expectation from Vega del Sella's model that the shell middens were cemented above the phreatic level. The combination of all these factors contradicts the assumption by Vega del Sella's model that the cementation occurred only after the occupations ceased and when the supposed original shell mound had grown until reaching the levels where we see it today in the karstic walls. More probably the cementation started already during the Mesolithic, as observed by González-Morales (1982), who linked that with Holocene rainfall increase, as it seems to be confirmed.

But our results have greater implications and raise a problem. Looking at the few examples in Fig. 3, it is obvious that something is missing because it was eroded. If everything missing was shell midden deposits, it is impossible that those shell middens were ever saturated, since their high porosity and permeability would always allow for water to drain, and phreatic conditions would not prevail. This leads us to questioning another recurrent assumption from uncritical acceptance of Vega del Sella's model, that everything missing was shelly deposits, envisioning a supposedly continuous volume of the shell mounds by the position where we find the cemented remnants today, hanging well above the ground. The question at this point is, was that missing something a huge shell mound that was filling all the available space we see empty today, from the level of the current ground up to the hanging remnant, as presumed by Vega del Sella? We argue that that is unlikely, because it is not supported by our evidence for phreatic conditions in spring environments. We argue, as a working hypothesis, that the ground level and topography we see today at most Asturian sites had different configurations in the Mesolithic, and could be much higher in some cases, at least near the cemented remnants. According to this hypothesis, that surface was eroded throughout the Late Holocene, leaving the already cemented remnants hanging in the walls, instead of a supposed shell mound that disappeared.

In other words, for the water table to be raise or perched at the level of the shell middens, some impermeable barrier would be needed at that level. That barrier could have been siliciclastic terrigenous deposits, over which the Mesolithic occupation took place, or, just as depicted by Vega del Sella, even previous Paleolithic layers. As mentioned before, the Asturian sites today are mainly recipients of rainwater and work as sinks, so the spring activity ceased at some point in the Mid-Late Holocene (hypothetically when the karstic systems became unsaturated, and the general water table level dropped). Once the spring activity ceased, it is possible that those hypothetical siliciclastic deposits, where the Mesolithic occupants lived, were eroded, possibly by mass movements towards the interior of the karstic conducts from where water was springing before. This seems to be supported by the fact that most Asturian sites present a slope going down into the karst, typically showing dense accumulations of clasts at the bottom in the contact with the wall (Figs. 3 and 6), that are the most recent deposits, from roofspall or rockfall, denoting a recent trend of sediments going in, not coming out. In sum, as represented by Fig. 19 (which, by the way, does not aim at replacing Vega del Sella's as a new paradigm), the hypothesis we wish to put forward, based on our geoarchaeological outcomes, is that the high position of some of the hanging remnants relatively to the current ground, could result from topographical features in the Mesolithic that subsided by erosion, during later stages of the Holocene and Historical periods. Such past topography had to be at a higher level to allow high water tables to impact the shell middens when the phreatic level raised, as opposed to massive anthropogenic accumulations envisioned based on the current ground, which in turn would allow for water drainage and prevent periodic inundation of the deposit. Let us analyse some upfront aspects that might contradict the theory we are putting forward.

4.3.3. How to explain that some Asturian shell middens are in contact with Paleolithic sequences that are not eroded (e.g., Balmori cave)?

An important aspect to point out is that we consider El Alloru and El Mazo to be representative of the most typical Asturian shell middens, those circumstances in which nearly 200 sites are found. Contrarily, the 1923 model is not representative of those, but it could indeed work in

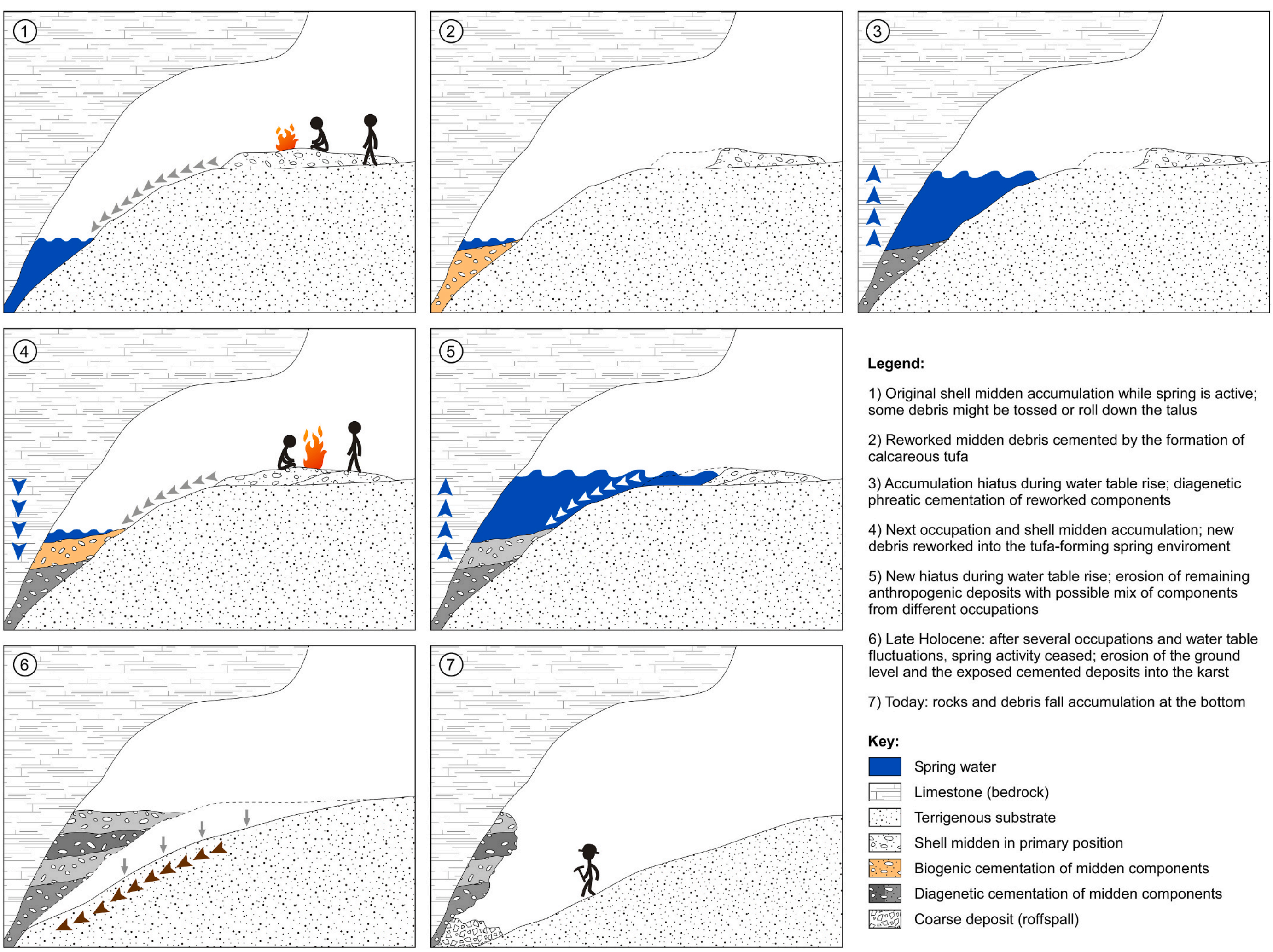

Fig. 19. Schematic representation of the hypothetical formation processes of the Asturian shell middens based on the micromorphological data from El Alloru and El Mazo; not to scale.

the very few cases of Asturian shell midden layers found on top of stratigraphic sequences originated in the Paleolithic. Such deposits are usually in inner areas of the karstic systems, or in topographically higher caves (e.g. La Garma) isolated from the spring activity, thus not affected by such processes. The sheltered areas occupied by Mesolithic hunter-gatherers were mostly more exterior. Therefore, our main critique is in interpreting hundreds of sites using a model built for sites in different conditions. Vega del Sella was not concerned about this; instead, he was pursuing evidence to know the age of the Asturian, and built the model based on the sites he excavated to tackle that, and without radiocarbon, he used the ones in stratigraphic framework. Those are less than ten (Clark, 1976; Clark and Clark, 1975; González Morales, 1982; Straus et al., 1981; Vega del Sella, 1930), in a universe of over two hundred Asturian sites. Furthermore, those Paleolithic cave deposits where geoarchaeological studies were carried out, are result of mass movements such as solifluction, debris and mud flows, from the outside into the caves (Álvarez-Fernández et al., 2018; Kehl et al., 2018; Pinto-Llona et al., 2012). In this frame it seems likely that the Mesolithic shell middens followed that trend and were also reworked into the karstic systems, occupying their place on top of the previously displaced deposits.

4.3.4. How to explain that some carbonate-cemented Asturian shell middens are overlying not carbonate-cemented deposits (e.g., La Riera)?

In these few cases, Vega del Sella's model might work, being in a position of the karstic system that was protected from the spring influence. The cementation of these layers could result from the development of speleothem formations from dripping water. But giving that those cases are a minority, it is more important, on light of our new outcomes, to highlight that most hanging Asturian shell middens unattached from a broader stratigraphic sequence, are reworked deposits and that spring activity likely changed continuously their original shape, distribution and overall spatial organisation. Thus, the practice of using the cemented remnants to envision oversized volumes or extensions of anthropogenic mounds should be cautious. That is why we do not wish to replace the model with a new one, since a wider sampling in Asturian sites is needed to get the widest possible range of possibilities for the formation processes of the shell middens, since as always in archaeology, each site tells its own story.

4.4. Future prospects

The new outcomes of this research give us much more valuable information for future studies. The carbonate-cemented Asturian shell middens must correspond to peripheral areas, when the spring systems were active, while the main human occupation took place in their proximity. This means that the carbonate cements in the Asturian deposits are much more significant than a mere post-depositional addition. As tufa deposits, these carbonate cements constitute excellent archives recording local changing environments, during which the human occupation does not seem to have ceased. Mineralogical and elemental analysis on the cements, for instance cathodoluminescence, can reveal hidden microfabrics and contribute to a more detailed understanding of their formation and diagenesis. Geochemical analysis such as stable isotopes and biomarkers analysis on the carbonate facies are a feasible research avenue to tackle palaeoevironemntal reconstruction (Dabkowski, 2014), namely rainfall regimes and vegetation, now that we know they are coetaneous of the Mesolithic occupations.

Within the plant record, this investigation yielded visible evidence of coralline seaweeds in the archaeological record of the Mesolithic, even if microscopic. The abundance of these elements alongside the shells at El Mazo and as burnt fragments within combustion residues fine-grained aggregates at El Alloru points to its presence in processing activities at the sites. In Iberia, there is evidence for Mesolithic consumption of freshwater plants by the Mesolithic population of the Sado shell middens (Buckley et al., 2023). The study of these components at El Mazo stratified non-cemented deposits will certainly contribute to expand on the possible use of this resource or the implications of its abundance.

It is indeed for future research to understand the sudden increase in Mesolithic shell middens in the Asturian area in respect to the previous Paleolithic record, but probably the answer lies in the main reason for fewer coastal Paleolithic sites in general: most of them might be submerged in the Bay of Biscay after the Holocene sea-level rise, alongside possible demographic growth in the Mesolithic or population movements towards coastal regions (García-Escárzaga et al., 2022; Marín-Arroyo, 2013). A more dynamic and dense population in the Asturian littoral platform took advantage of the ecotone conditions with easy access to marine, forest, and freshwater resources nearly everywhere, using the numerous sheltered spots in the heavily karstified topography, sometimes, where Paleolithic occupations had also occurred. For now, we understand better the internal context of the Asturian. Hopefully, this new data will help in further expand the broader context of these Holocene hunter-gatherers and their role, or fate, in the next fundamental step in societal evolution – the Neolithic.

5. Conclusion

Before the synthesis on the Asturian about a century ago, Vega del Sella (1914) published the first Asturian context, the cave of Penicial. By then he cautiously didn't attempt a chronological attribution for lack of a secure stratigraphy, but now that the age of this technology is known, it is interesting that he does not mention any carbonate cementation of this context, which is in an outer rockshelter, where he identified fireplaces associated to the tools but took it with equal caution: "Though the place where [the stone tools] appeared is close to the fireplaces, given the runoff verified there, it would be foolhardy to consider them coetaneous" (free translation from the Spanish original).

It seems like being more towards the open-air areas or the sheltered areas was not an issue of particular concern to the Asturian hunter-gatherers. El Alloru's occupation surface was apparently poor in shellfish remains, but intensely frequented, suggesting a likely location of the shell middens and combustion features later redeposited somewhere in between this point and the back of the rockshelter, where the spring was active and cementing occupational debris that ended up there. Like we have hinted at the beginning, probably Vega del Sella was puzzled by non-existence of dwelling features in the Asturian layers, in contrast to the Paleolithic ones in caves, and that made him wonder, not without reason. Those traces are embedded in the shell middens but were invisible to his eyes.

The regional, and original, homogeneity of the Asturian record can only be explained by factors of climatic and geological order, such as the rainfall rates that control hydrological and spring activity, to explain generalised erosive events at regional scale. The differences in local environment and higher or lesser direct influence of anthropogenic actions in the accumulation of the deposits between El Alloru and El Mazo, demonstrates that Asturian shell middens need to be addressed individually to get the most of its informative potential, particularly when they usually constitute the only remains of the intense Mesolithic occupation of the region. The study of the early Holocene increase in hydrological activity in the littoral of Asturias has been hampered by the fact that tufa buildups are much better preserved and known in the opposite side of the Cantabrian Mountains, drained by the Ebro basin (e.g., González-Amuchastegui and Serrano, 2015), than in the Bay of Biscay watersheds, where evidence of such past intense hydrological activity is not as obvious. This is noticeable in all Asturian sites, such as El Alloru and El Mazo, that also provided an answer: it is the cemented shell middens that are masking the early-mid Holocene tufa formations, as an early example of human activity shaping the geological record at regional level, much like an early example at regional scale of what is now generalised as *Anthropocene*.

Declaration of competing interest

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

Data availability

The micromorphological samples used in this study are curated at the Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour at the University of Algarve, Faro, Portugal.

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Appendix A. Supplementary data

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