



Shellfish procurement and seasonal scheduling across the Mesolithic–Neolithic transition at Zacatín rock shelter (Gualchos-Castell de Ferro, Granada, southern Iberia)[☆]

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ABSTRACT

This study investigates the intertidal shellfish exploitation by the last hunter-gatherers and the first farmers, and their role within broader subsistence strategies during the Mesolithic–Neolithic transition on the Mediterranean coast of the Alboran Sea. We conducted taxonomic, biometric, and stable oxygen isotope ratio ($\delta^{18}\text{O}$) analyses of *Patella caerulea* Linnaeus, 1758, shells recovered from the Zacatín rock shelter (Granada, southern Iberia). Shell $\delta^{18}\text{O}$ values indicate that shellfish harvesting did not occur uniformly throughout the year but was concentrated in colder months, suggesting seasonal visits to the coast. Comparable seasonal patterns are observed in both Mesolithic and Early Neolithic levels, pointing to continuity in the timing of intertidal resource use despite the introduction of farming and herding practices. This marked seasonal collection is discussed in relation to taxonomic diversity and shell size variations observed at the site, as well as to different approaches to environmental availability and subsistence organisation within broader economic strategies.

1. Introduction

The 'Neolithisation' of the Iberian Peninsula was a pivotal process marked by significant economic and social changes. It was characterised by an increase in sedentism, the adoption of agriculture and livestock farming, and the development of new production technologies and organisational structures. Archaeological research has demonstrated that this process was neither homogeneous nor linear. Instead, it developed along diverse regional trajectories in which innovations associated with the peasant economy were unevenly integrated into existing economic and cultural practices (Cubas et al., 2016; Saña et al., 2020). Consequently, Neolithisation should be understood as a process of change in which practices inherited from hunter-gatherer societies coexisted with new strategies for managing resources and territory.

In this context, coastal exploitation is a relevant area in which to assess the scope and nature of changes during the Mesolithic–Neolithic

transition. The Iberian Peninsula's diverse coastal environments have generated a rich archaeological record, providing valuable insights into the role of marine resources in early Holocene subsistence strategies (Álvarez-Fernández, 2011; 2015; 2025; Colonese et al., 2011; Gutiérrez-Zugasti et al., 2011; Jordá Pardo et al., 2016; Román et al., 2022; Verdún-Castelló et al., 2019). A recently published review (Aguirre-Uribesalgo et al., 2024) examining the exploitation of marine molluscs during the Mesolithic–Neolithic transition on the Iberian Peninsula found that, while these resources were consumed throughout the Neolithic period, there were changes in the quantitative importance and diversity of species. Generally, Neolithic assemblages are dominated by a small number of taxa (mainly *Patella* and *Phorcus* genus), whereas Mesolithic contexts exhibit a more diverse composition, with substantial geographic variability. In the Cantabrian region, for example, *Patella* (particularly *Patella depressa* Pennant, 1777, and *Patella vulgata* Linnaeus, 1758) and *Phorcus lineatus* (da Costa, 1778), predominate in both

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periods. In other areas, such as the Atlantic and Mediterranean coasts, Mesolithic assemblages exhibit greater taxonomic diversity (in addition to *Patella* and *Phorcus* genus, *Mytilus* and *Cerastoderma* genus and *Stramonita haemastoma* [Linnaeus, 1767]). During the Neolithic period, however, a greater concentration of certain taxa is observed, including *Patella*, *Mytilus* and *Phorcus turbinatus* (Born, 1778). Notably, Neolithic sites in the Gulf of Cádiz exhibit relatively diverse associations, with taxa such as *Ruditapes decussatus* (Linnaeus, 1758), *Solen marginatus* Pulteney, 1799, and *Hexaplex trunculus* (Linnaeus, 1758), playing a significant role without any single taxon dominating the assemblage.

In summary, these patterns suggest that the establishment of farming did not involve abandoning the use of marine resources. Molluscs that were harvested by Mesolithic populations continued to be collected by Neolithic farmers, although some changes appear to have occurred as a function of ecological niches. In general, however, taxa such as *Patella* and *Phorcus* continued to be consumed.

This trend has been linked to environmental and economic factors. Environmental factors include changes in the availability of intertidal resources due to aridification processes, the loss of coastal plains, and the transformation of coastal ecosystems (Brisset et al., 2022). Economic factors include the introduction of agricultural and livestock practices, as well as the reorganization of exploitation territories. Changes in settlement patterns may also have influenced collection and transport strategies in relation to distance from the coastline, favouring species with better preservation potential or non-food uses (Aguirre-Urbesalgo et al., 2024; Bicho et al., 2010; Fernández-López de Pablo and Gabriel, 2016).

However, establishing the economic importance of marine resources in prehistoric subsistence strategies involves more than merely identifying continuities or changes in assemblage composition. It is possible that their role was redefined in the context of agricultural and livestock productions, which introduced different approaches to task organisation

and risk management (Aguirre-Urbesalgo et al., 2024). From this perspective, marine resources may have served various purposes. These include short-term protein suppliers, acting as a backup resource in the event of production shortfalls, promoting economic diversification, and ensuring the continuity of earlier traditions (Bailey, 2004; Erlandson, 2001; Mannino et al., 2011). Therefore, to assess their integration into Neolithic economies, it is essential to determine whether their exploitation was opportunistic or planned, and to establish the seasons in which this occurred. In this context, establishing the seasonality of mollusc harvesting is crucial.

Although stable oxygen isotope ratio ($\delta^{18}\text{O}$) analyses have proven effective for this purpose (Andrus, 2011; Leng and Lewis, 2016), they have mainly been applied in the Atlantic region of the Iberian Peninsula (García-Escárcaga et al., 2019; 2024a; 2025; Arniz-Mateos et al., 2026), while the Mediterranean coasts of Iberian Peninsula remains largely undocumented. The Zacatín rock shelter in Granada, Spain, offers an exceptional opportunity in respect of this, as it contains a clearly defined stratigraphic sequence including evidence of the last hunter-gatherer societies and the first farming communities in the Alboran Sea region (Martínez Sánchez et al., 2024) (Fig. 1). The excellent preservation of the malacological remains, coupled with comparable Mesolithic and Neolithic levels, enables diachronic analysis to be conducted within the same site and under similar environmental conditions.

The main objective of this study is to assess whether the adoption of domesticated species and, more broadly, agriculture and livestock farming, led to significant changes in the exploitation of coastal resources at the beginning of the Holocene in southern Iberia. To this end, the following specific objectives have been proposed: (1) analyse the composition and variability of malacological assemblages found at Mesolithic and Neolithic levels in the Zacatín rock shelter; (2) evaluate possible changes in management strategies for intertidal species, paying particular attention to the *Patella* genus; (3) determine seasonal



Fig. 1. Geographic location of the Zacatín rock shelter (Granada, southern Spain). A) on the Iberian Peninsula, (B) on the Alboran Sea north coast, and (C) on the cliffs north of Torre del Zambullón, between Calahonda Beach and Zacatín cove.

harvesting patterns using sequential $\delta^{18}\text{O}$ analysis; and (4) discuss the role of coastal resources in the Neolithic transition in southern Iberia more broadly, considering their potential contribution to economic diversification and risk management.

This study presents the results of a sequential $\delta^{18}\text{O}$ analysis of *Patella caerulea* Linnaeus, 1758 shells found in the Mesolithic and Neolithic stratigraphic units of the Zacatín rock shelter. Intra-shell $\delta^{18}\text{O}$ values recorded during shell growth reflect seasonal variations in sea surface temperature throughout the molluscs' lifetimes, allowing us to estimate the time of year at which this shellfish species was harvested by the last hunter-gatherers and the first farming communities (Andrus, 2011; García-Escárcaga et al., 2025; Leng and Lewis, 2016). This approach provides a direct empirical basis for assessing possible changes in the temporal organisation of intertidal resource exploitation during the Mesolithic-Neolithic transition in southern Iberia, where this type of evidence is scarce.

2. Materials and methods

The assemblages and samples analysed in this study come from the Zacatín rock shelter. Located in a coastal cliff environment, the shelter is one of the few stratified contexts in the south of the peninsula that provides evidence of both hunter-gatherer societies and the first

Neolithic communities. In 2019, the site was the subject of an archaeological intervention motivated by the state of conservation of the deposit and the need to document the preserved stratigraphic sequence. This intervention revealed a sequence comprising four major stratigraphic phases. This study focuses exclusively on the three oldest phases, which correspond to the Mesolithic period and two phases of the Early Neolithic period (Martínez Sánchez et al., 2024) (Fig. 2).

The basal level (Phase 1, 6800–5700 cal BC) corresponds to a Mesolithic occupation characterised by a shell midden with a high proportion of marine remains. There is no direct evidence of animal or plant domestication. Radiocarbon dating suggests the possibility of two main occupation episodes: the first in the 7th millennium BC and the second spanning the late 7th to the first third of the 6th millennium BC. However, in the absence of diagnostic archaeological materials, this subdivision should be regarded as a plausible hypothesis based primarily on the radiocarbon evidence. This sequence is one of the few examples of stratified evidence of Mesolithic occupation on the Andalusian Mediterranean coast (Martínez Sánchez et al., 2024).

Two phases attributed to the Early Neolithic developed on this horizon: Phase 2 (Early Neolithic 1, c. 5600–5300 cal BC) and Phase 3 (Early Neolithic 2, c. 5200–4800 cal BC). These phases are characterised by horizontal layers that indicate repeated occupation during the early development of farming economies in the area. The levels have

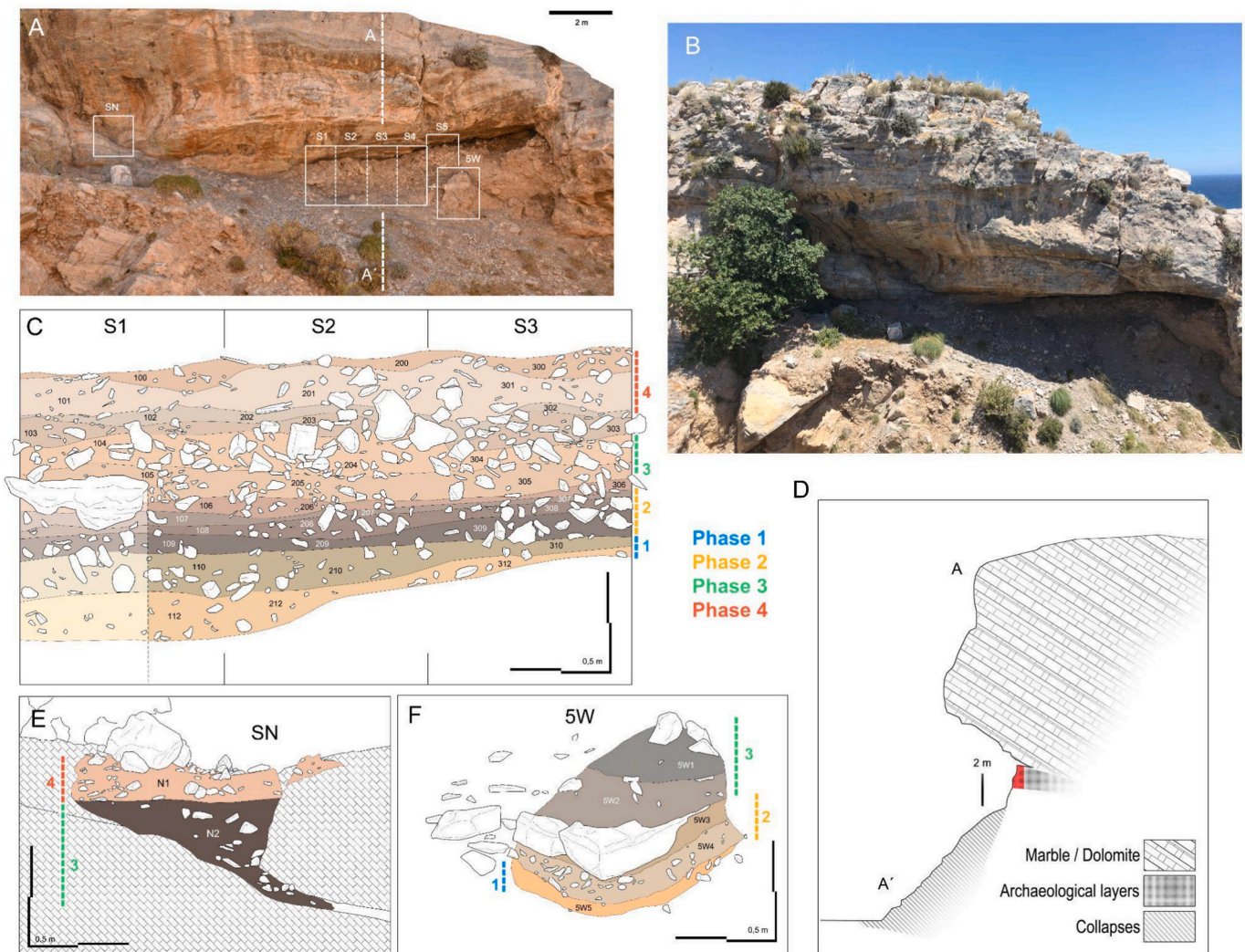


Fig. 2. A, C, E, F: Stratigraphic sequence of the Zacatín rock shelter showing the main archaeological units and the phases defined in this study. Phase 1 (blue): Mesolithic; Phase 2 (yellow): Early Neolithic 1; Phase 3 (green): Early Neolithic 2; Phase 4 (red): Historic/ Mixed levels (not considered in this study). B: General view of the site in 2018. D: Schematic drawing of the rockshelter section (Martínez Sánchez et al., 2024).

produced pottery decorated with impressions and incisions, as well as carved stone tools, shell beads and the remains of domesticated animals and cultivated cereals (Martínez Sánchez et al., 2024). This allows the levels to be assigned to the Early Neolithic period in southern Iberia. The chronological results place the Early Neolithic phases between the middle of the 6th millennium and the beginning of the 5th millennium BC. This is consistent with the regional Neolithisation framework in southern Iberia (Aura et al., 2013; García-Martínez de Lagrán et al., 2018; Martín-Socas et al., 2018). The set of radiocarbon data used in this study is presented in Table 1 and Fig. 3, which show the stratigraphic units and the corresponding calibrated chronological ranges.

2.1. The archaeomalacology set: Taxonomy and biometrics

A total of 6265 marine shell remains have been recovered at the site, from which a total of 4066 individuals have been identified, belonging to a total of 27 different taxa (Aguirre-Uribesalgo, 2024; Martínez Sánchez et al., 2014). In this paper taxonomic determinations based on the minimum number of individuals (MNI) following Moreno-Nuño (1994) were carried out. These differentiate *P. caerulea* from the rest of the limpets documented in the three prehistoric phases of Zacatín. Together with quantitative analysis, they are used to assess species composition and their relative frequencies across the different stratigraphic levels. In addition, a biometric study was undertaken to evaluate temporal variation in shell size. Measurements were obtained with a digital calliper accurate to 0.01 mm, following the procedures described for gastropods and bivalves (Gutiérrez-Zugasti, 2011; Álvarez-Fernández et al., 2011). Diversity indices were calculated to characterise the community structure and to assess whether exploitation responds to a broad-spectrum, groups with several species and without a clear dominance in one of them, or specialised management strategy, focusing on a limited number of species. The following indices were applied to this end: the Simpson dominance index ($D = \sum p_i^2$), the Shannon–Weiner index ($H' = -\sum p_i \ln p_i$), Pielou's evenness ($J = H'/\ln S$) and true diversity of order 1 (${}^1D = \exp[-\sum p_i \ln p_i]$), following Moreno (2001), Jones (2004) and Faith and Du (2018).

2.2. *Patella caerulea* shells from Zacatín site

P. caerulea (Fig. 4A) was one of the most represented marine mollusc species in both Mesolithic and Neolithic units of Zacatín (Aguirre-Uribesalgo, 2024), thereby providing a robust sample for analysing patterns of shellfish collection. This limpet species, which is endemic to the Mediterranean Basin, is distributed across rocky intertidal shores, from the mid-littoral to the infralittoral zone (Davies, 1969; Mauro et al., 2003). A previous sclerochronological study using modern mollusc individuals from the central and western Mediterranean demonstrate that $\delta^{18}\text{O}$ values from this taxon reliably record seawater temperature annual variations throughout the mollusc's lifespan (Prendergast and Schöne, 2017). Although episodes of slow growth or minor growth cessation

were observed in some modern specimens, the isotopic values obtained from the shells recorded the annual temperature maxima and minima and accurately reflected the harvesting season (Ferguson et al., 2011; Prendergast and Schöne, 2017). These results confirmed that $\delta^{18}\text{O}$ values from *P. caerulea* are a reliable proxy for reconstructing past environmental conditions, as well as for determining the season of mollusc collection by prehistoric societies across the Mediterranean Basin.

In our study, a total of 10 shell samples were recovered from each of the three phases considered here, in order to reconstruct patterns of seasonal littoral resource exploitation during the Mesolithic Phase 1, the Archaic Early Neolithic Phase 2 (Early Neolithic 1), and the Evolved Early Neolithic Phase 3 (Early Neolithic 2) (Fig. 2C). Specimens were selected based on conservation, taphonomy, and stratigraphy criteria. Only complete or nearly complete shells retaining the rim and the axis of maximum growth were selected. Furthermore, only *P. caerulea* shells without visible taphonomic alterations such as decalcification, encrustation, abrasion, bioerosion, or burning, were considered. Experimental studies on marine gastropod shells have shown that heating-induced mineralogical transformations are generally associated with visible and microstructural alterations (Milano et al., 2016; Milano and Nehrke, 2018), supporting the suitability of the selected specimens for isotopic analysis. Samples were obtained from archaeological units assigned to each chronological phase (UE 212, UE 209, and UE 206–205), prioritizing, whenever possible, contexts directly associated with radiocarbon dates. All analyzed specimens came from Sector 2, thus minimizing the possibility of stratigraphic intrusion from adjacent areas.

2.3. Shell sampling procedures and stable oxygen isotope analyses

To obtain a cross-section representative of overall shell growth and following a previous sclerochronological study of this taxon (Prendergast and Schöne, 2017), limpets were transversely sectioned along the axis of maximum growth using a Buehler IsoMet saw fitted with a 120 μm diamond disc operated at low speed (Fig. 4A). Subsequently, as in previous isotopic studies on limpets (García-Escárcaga et al., 2020, 2024b; Marchán-Fernández et al., 2025), carbonate micro-samples for stable oxygen isotope analyses were extracted along the shell growth axis, from the shell edge, representing the last portion of shell deposited prior to mollusc collection, toward the shell apex. Two complementary sampling strategies were employed. The first micro-sample of each isotopic series was manually obtained by milling the innermost portion of the shell edge using a dentist microdrill equipped with a 1 mm diamond bit. For long isotopic sequences, the remaining micro-samples were subsequently extracted along the axis of shell growth from the concentric cross-foliated calcite layer M + 2 (Fenger et al., 2007), which was specifically selected because previous studies have demonstrated that this layer is composed entirely of primary calcite in several *Patella* species (García-Escárcaga et al., 2020, 2024b; Demarchi et al., 2013; Prendergast and Schöne, 2017), thereby

Table 1

List of radiocarbon determinations from short-lived samples associated with phases 1, 2 and 3 of the Zacatín rockshelter (Martínez Sánchez et al., 2024). Calibrations were carried out using the IntCal20 curve (Reimer et al., 2020) and OxCal v.4.4 (Bronk Ramsey, 2009). * The radiocarbon date was obtained from dentine extracted from faunal teeth.

Phase	Stratigraphic Unit (UE)	Lab code	Material dated	14C age (BP $\pm 1\sigma$)	Cal BC (68.2 %)	Cal BC (95.4 %)
3	104	Beta-559759	<i>Bos</i> sp., tooth*	5970 ± 30	4899–4797	4945–4730
3	N2	Beta-561489	<i>Capra hircus</i> , mandible	6220 ± 30	5289–5074	5301–5054
2	5 W3	Beta-542745	<i>Caprinae</i> , humerus	6370 ± 30	5374–5311	5471–5222
2	209	Beta-573494	<i>Fabaceae</i> , charcoal	6520 ± 30	5528–5410	5557–5381
2	207	Beta-586169	<i>Olea europaea</i> , charcoal	6610 ± 30	5614–5485	5620–5481
2	5 W4	Beta-573493	<i>Pistacia lentiscus</i> , charcoal	6710 ± 30	5656–5569	5711–5561
1	5 W5	CIRAM-14895	Monocot, charcoal	6870 ± 36	5796–5751	5839–5716
1	112	Beta-573495	<i>Pistacia lentiscus</i> , charcoal	7140 ± 30	6057–5987	6067–5926
1	310	Beta-586168	<i>Olea europaea</i> , charcoal	7850 ± 30	6641–6597	6816–6597
1	212	Beta-561490	<i>Fabaceae</i> , charcoal	7880 ± 30	6771–6649	7023–6641

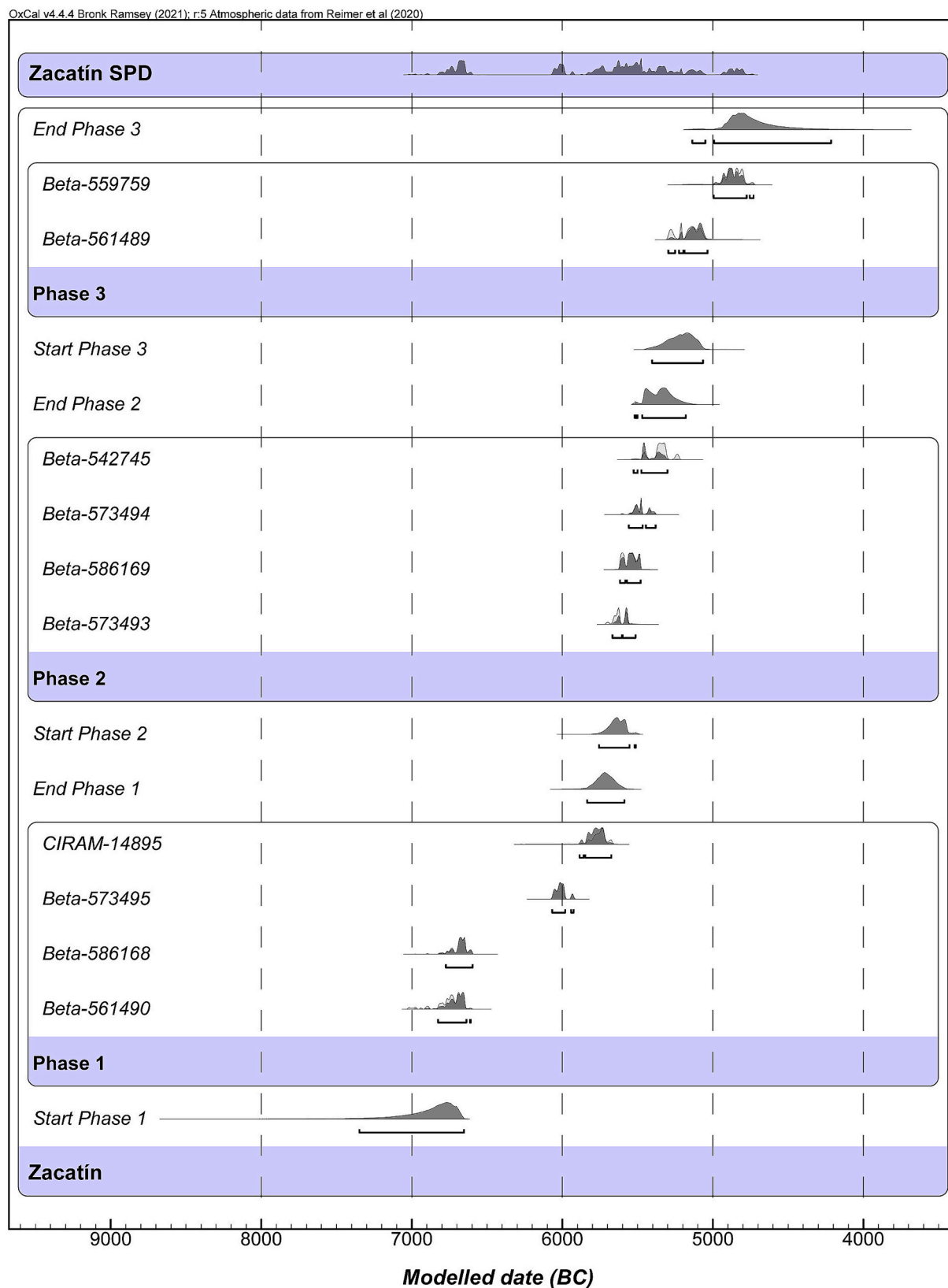


Fig. 3. Radiocarbon determinations from short-lived samples recovered in phases 1, 2 and 3 of the Zacatín rockshelter. Dates were calibrated using the IntCal20 curve (Reimer et al., 2020) and OxCal v.4.4. (Bronk Ramsey, 2009). The figure presents the overall summed probability distribution for the site (upper panel), the phase-based summed probability distributions (lower panels), and individual calibrated radiocarbon date plots.

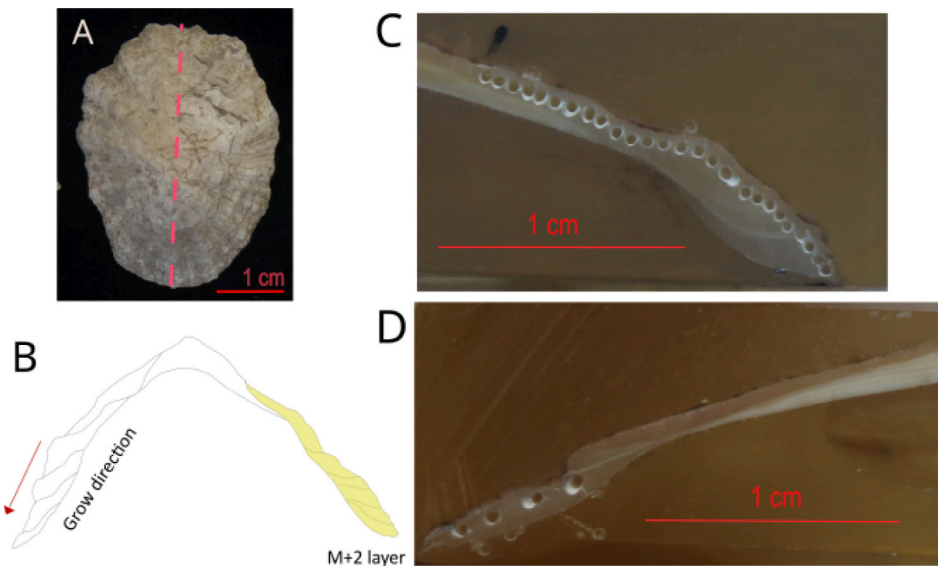


Fig. 4. A: *Patella caerulea* shell sample. B: Section of a *Patella caerulea* shell highlighting the M + 2 layer, from which carbonate samples were taken for isotopic analyses. C, D: Nine short and one long $\delta^{18}\text{O}$ series were obtained for each archaeological phase.

minimizing the risk of isotopic alteration associated with mineralogical transformation during diagenesis. Samples were collected at 0.5 mm intervals using a hand-held microdrill with a 0.4 mm tungsten drill bit mounted on a stereomicroscope. For short isotopic sequences, four micro-samples were extracted following the same procedure, but at variable intervals ranging from 0.5 to 1 mm, depending on shell growth structure and the spacing of successive growth increments. Using this sampling strategy, one specimen per unit yielded long isotopic series comprising between 19 and 28 carbonate micro-samples (Fig. 4C), whereas the remaining nine specimens per stratigraphic unit yielded a short series of five micro-samples each (Fig. 4D) (García-Escárcaga et al., 2024a; Marchán-Fernández et al., 2025; Arniz-Mateos et al., 2026).

A total of 205 micro-samples were taken from *P. caerulea* specimens analysed in this investigation. For each micro-sample, at least 200 μg of carbonate powder were collected and stored in 1.5 mL glass vials prior to analysis. Shell $\delta^{18}\text{O}$ values were measured at the IsoTopik Lab at the University of Burgos (Spain), using a Thermo Scientific Delta V Plus IRMS coupled to a Gas Bench II Interface. The average precision (1σ ; computed from eight measurements per sample) was systematically better than $\pm 0.06\text{‰}$. Oxygen isotope ratios results were calibrated against NBS-18 ($\delta^{18}\text{O}_{\text{VPDB}} = -23.2\text{‰}$), IAEA-603 ($\delta^{18}\text{O}_{\text{VPDB}} = -2.37\text{‰}$), and IAEA-CO-8 ($\delta^{18}\text{O}_{\text{VPDB}} = -22.7\text{‰}$) primary standards. All $\delta^{18}\text{O}$ values are reported in per mil (‰) relative to the Vienna Pee-Dee Belemnite (VPDB) standard.

2.4. Determination of *Patella caerulea* collection season(s)

To determine the season during which marine limpets were harvested, we applied a methodological framework based on the quartile system first developed by Mannino et al. (2003) and subsequently adopted in multiple isotopic studies (Arniz-Mateos et al., 2026; Colonese et al., 2018; García-Escárcaga et al., 2019; Marchán-Fernández et al., 2025; Prendergast et al., 2016). Briefly, the expected intra-annual $\delta^{18}\text{O}$ ranges for each unit were calculated independently using all available $\delta^{18}\text{O}$ values derived from both long and short isotopic sequences obtained for each unit and subsequently divided into four quartiles, each broadly corresponding to a season. Because $\delta^{18}\text{O}$ values are inversely correlated with seawater temperature, the upper quartile corresponds to colder periods (i.e., winter), whereas the lower quartile is associated with warmer conditions (i.e., summer). Consequently, $\delta^{18}\text{O}$ measurements taken at the shell margin that fall within the highest or lowest quartiles indicate collection during winter or summer, respectively.

Values located within the intermediate quartiles are attributed to autumn or spring, depending on the directional pattern of the sequential $\delta^{18}\text{O}$ values prior to the shell edge: a progressive increase toward the margin suggests autumn, while a decreasing trajectory indicates spring.

3. Results

Gastropods predominated by far, representing over 80 % of the assemblage at Zacatín, while bivalves accounted for the remaining 20 %. The complete dataset (NISP and MNI by stratigraphic phase and by species/family) is provided in the supplementary material (Table S1). Regarding limpets, taking into account the MNI, among gastropods they represent 93.02 % in Phase 1, 94.95 % in Phase 2 and 93.53 % in Phase 3. Among limpets, and taking into account also the MNI, *P. caerulea* is represented in Phase 1 by 16.7 %, in Phase 2 by 19.07 % and in Phase 3 by 17.77 %, respectively.

During the Mesolithic (Phase 1; MNI = 1,207), the sample was more diverse and balanced (25 taxa), with significant representation, among the non-gastropod taxa, of the *Mytilidae* family (approximately 16 % of the MNI). During Early Neolithic 1 (Phase 2; MNI = 1,726), the proportion of *Patellidae* increased from 74 % in Phase 1 to 85.22 % in Phase 2 (based on MNI), while the proportion of *Mytilidae* decreased to 10.31 %. This reduced the number of taxa to 21. This trend intensified during the Early Neolithic 2 period (Phase 3; MNI = 1,133), with gastropods accounting for around 98 % of the MNI and bivalves decreasing to residual values of less than 2 %. This resulted in a reduction in richness to 19 taxa.

The diversity indices reinforce this pattern (Table 2). Taxonomic

Table 2
Taxonomic diversity indices of the faunal assemblage for the Mesolithic (1), Early Neolithic 1 (2), and Early Neolithic 2 (3).

Indicator	Mesolithic	Early Neolithic 1	Early Neolithic 2
NISP	1207	1726	1133
Number of taxa	25	21	19
D (Simpson index)	0,611	0,735	0,846
1/D (Inverse Simpson index)	1,637	1,361	1,181
H' (Shannon index)	0,966	0,635	0,446
J' (Pielou's evenness)	0,317	0,224	0,165
qD (Effective number of species)	2,626	1,886	1,562

richness decreases progressively over time (from 25 to 21 to 19), while the Simpson index (D) increases (from 0.611 to 0.735 to 0.846), indicating greater dominance. The Simpson inverse (D') also demonstrates a continuous decrease (from 1.637 to 1.181), as does the effective number of species (S') (from 2.626 to 1.562). Similarly, the Shannon (H') and Pielou (J') values decrease progressively, indicating a loss of evenness. Overall, the results show a change from a more diverse assemblage in the Mesolithic to the increasingly concentrated exploitation of a few species in the Early Neolithic period, especially in its final stage.

The shell length was analysed for three *Patella* species across three chronological phases (Mesolithic, Early Neolithic 1 and Early Neolithic 2). Descriptive statistics are presented in Table 3. Given the strong correlation between length and width in the three species (Spearman Rs = 0.965 in *P. caerulea*, 0.974 in *Patella ulyssiponensis* Gmelin, 1791, and 0.970 in *Patella rustica* Linnaeus, 1758), maximum length was used as the main proxy for assessing diachronic changes in shell size (Fig. 5).

For *P. caerulea*, shell length ranges from 18.00 to 46.71 mm in the Mesolithic phase (n = 113), from 19.20 to 46.42 mm in Early Neolithic 1 (n = 188), and from 17.03 to 40.54 mm in Early Neolithic 2 (n = 104). Median values are similar across phases, ranging between 26.49 and 26.72 mm.

For *P. ulyssiponensis*, shell length ranges from 16.04 to 43.37 mm in the Mesolithic phase (n = 166), from 17.77 to 45.27 mm in Early Neolithic 1 (n = 156), and from 16.03 to 41.36 mm in Early Neolithic 2 (n = 60). Median values vary between 24.57 and 25.16 mm.

For *P. rustica*, shell length ranges from 15.51 to 34.20 mm in the Mesolithic phase (n = 167), from 14.59 to 38.74 mm in Early Neolithic 1 (n = 247), and from 16.02 to 37.79 mm in Early Neolithic 2 (n = 127). Median values range between 23.05 and 23.75 mm.

Kruskal–Wallis tests were performed to evaluate differences in shell length between phases for each species. No statistically significant differences were detected for *P. caerulea* (H = 1.55, p = 0.46), *P. ulyssiponensis* (H = 1.59, p = 0.45), or *P. rustica* (H = 1.07, p = 0.58).

The $\delta^{18}\text{O}$ records obtained from the shells of 30 *P. caerulea* specimens reflect variations in sea surface temperature throughout the individuals' life span, making them suitable for identifying the season of mollusc collection (Supplementary Material Fig. S1). The annual extremes in seawater temperature, corresponding to winter, the coldest months, and summer, the warmest months, are clearly distinguishable, along with the transitional warming in spring and cooling in autumn. Maximum and minimum $\delta^{18}\text{O}$ values obtained from the three phases are quite similar (Table 4), and consequently, the $\delta^{18}\text{O}$ ranges from these units also show close agreement (Mesolithic: 3.17 ‰; Early Neolithic 1: 3.06

Table 3

Summary statistics of shell length (mm) for three *Patella* species across the three sampling phases. Values include sample size (n), median, mean $\pm$ standard deviation (SD), and observed range.

Species	Phase	n	Median (mm)	Mean $\pm$ SD (mm)	Min–Max (mm)
<i>Patella caerulea</i>	1	113	26.51	27.75 $\pm$ 6.15	18.00–46.71
<i>Patella caerulea</i>	2	188	26.72	27.47 $\pm$ 5.05	19.20–46.42
<i>Patella caerulea</i>	3	104	26.49	26.60 $\pm$ 4.85	17.03–40.54
<i>Patella ulyssiponensis</i>	1	166	25.16	26.18 $\pm$ 5.35	16.04–43.37
<i>Patella ulyssiponensis</i>	2	156	24.57	25.46 $\pm$ 4.94	17.77–45.27
<i>Patella ulyssiponensis</i>	3	60	24.69	26.15 $\pm$ 5.82	16.03–41.36
<i>Patella rustica</i>	1	167	23.75	23.74 $\pm$ 3.49	15.51–34.20
<i>Patella rustica</i>	2	247	23.05	23.73 $\pm$ 4.64	14.59–38.74
<i>Patella rustica</i>	3	127	23.74	24.00 $\pm$ 4.39	16.02–37.79

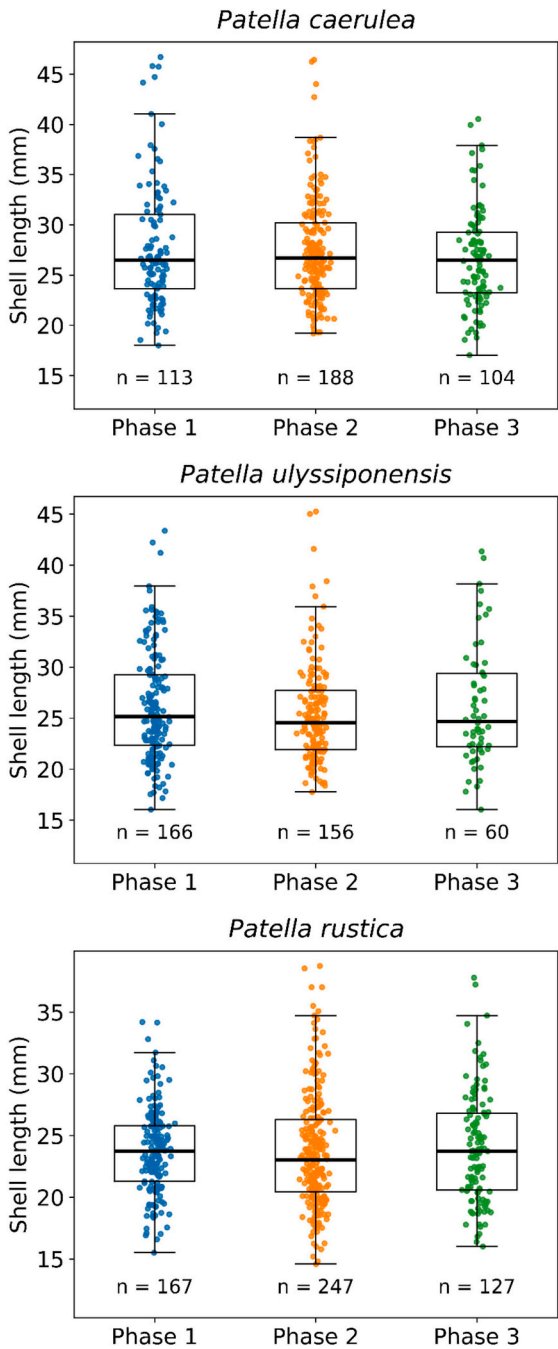


Fig. 5. Shell length distributions of *P. caerulea*, *P. ulyssiponensis* and *P. rustica* by chronological phase (Mesolithic – Phase 1; Early Neolithic 1 – Phase 2; Early Neolithic 2 – Phase 3). Boxplots show the median (black line), interquartile range (box) and 1.5 $\times$ IQR whiskers.

‰; Early Neolithic 2: 3.26 ‰). The quartile range values derived from the maximum and minimum $\delta^{18}\text{O}$ values for each unit, which are needed to estimate the season when each mollusc specimen was collected, are also shown in Table 4.

The isotopic data obtained from the edges of the limpets (Fig. 6A), which represent the last portion of mollusc growth, showed both high and low $\delta^{18}\text{O}_{\text{shell}}$ values, indicating that *P. caerulea* were harvested throughout the year. Nevertheless, the number of specimens is not uniformly distributed across the four seasons with the coldest months (winter), showing the highest shellfish exploitation during the Mesolithic and Early Neolithic, consistently representing around 60 % of the total (Fig. 6B–D). Summer and autumn are also regularly represented,

Table 4

Maxima and Minima $\delta^{18}\text{O}_{\text{shell}}$ values obtained from all analysed *Patella caerulea* specimens for each SU, together with the isotopic ranges of the upper, middle, and lower quartiles estimated for each SU using both long and short isotopic series from Mesolithic, Early Neolithic 1 and Early Neolithic 2 archaeological phases (Table S2).

Chronology	Maximum $\delta^{18}\text{O}_{\text{shell}}$ value	Minimum $\delta^{18}\text{O}_{\text{shell}}$ value	Upper quartile (winter)	Intermediate quartiles (spring – autumn)	Lower quartile (summer)
Mesolithic	2,07	−1,10	2.07 – 1.28 ‰	1.27 – −0.32 ‰	0.31 – −1.10 ‰
Early Neolithic 1	2,12	−0,94	2.12 – 1.36 ‰	1.35 – −0.19 ‰	0.18 – −0.94 ‰
Early Neolithic 2	2,17	−1,09	2.17 – 1.36 ‰	1.35 – −0.29 ‰	0.28 – −1.09 ‰

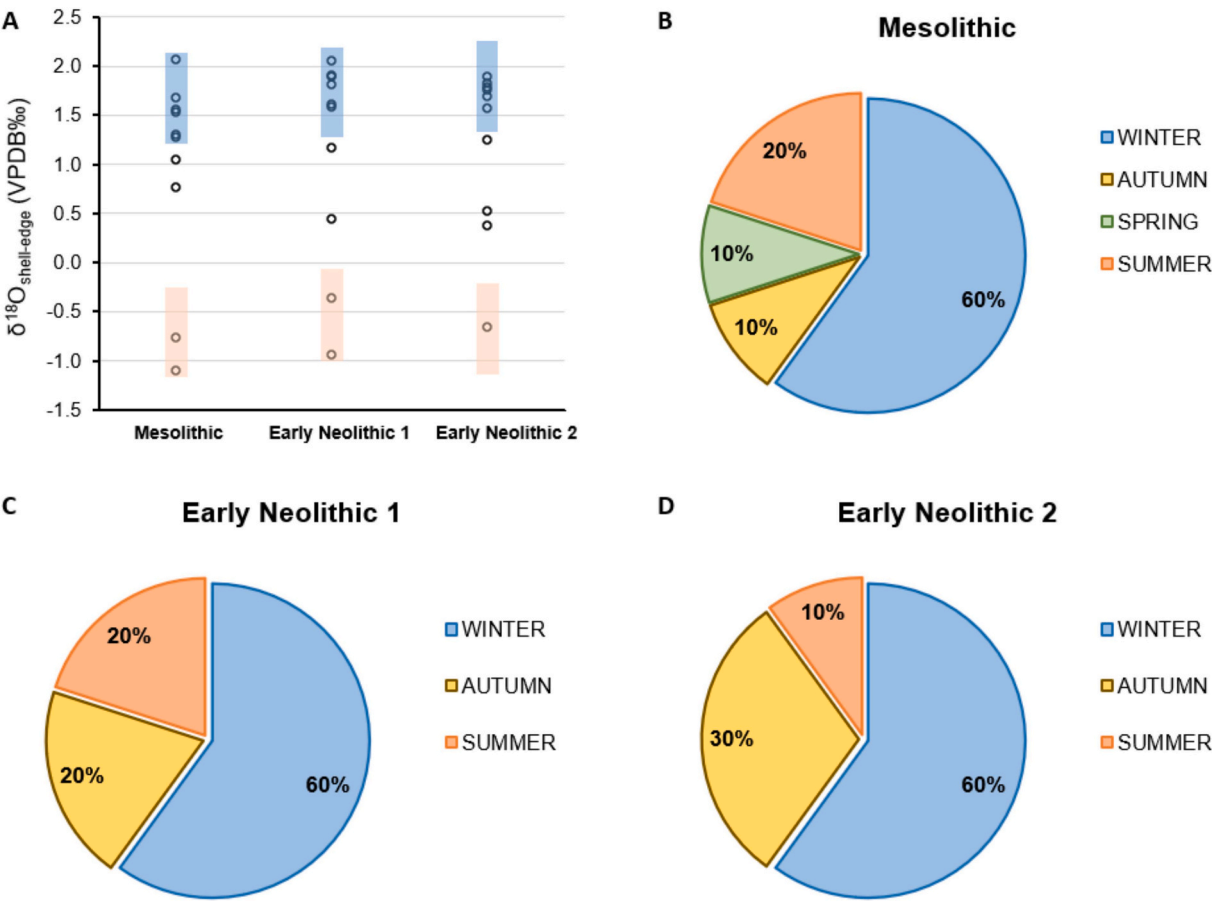


Fig. 6. A: $\delta^{18}\text{O}$ values from the edges of the *P. caerulea* limpets from the Mesolithic and Early Neolithic stratigraphic units. Blue and orange rectangles indicate the upper and lower quartile ranges, representing the winter and summer seasons, respectively. Pie charts show the percentage of shells assigned to each season according to the quartile method in the Mesolithic (B), Early Neolithic 1 (C), and Early Neolithic 2 (D) chronological horizons.

although their proportions vary over time, remaining below 20 % and 30 %, respectively, while spring is only present during the Mesolithic. Despite limpets being collected during all seasons, harvesting activities primarily occurred during the colder months. Overall, 80 % and 70 % of the molluscs were collected during the coldest half of the year, from late autumn to early spring, during Mesolithic and Early Neolithic, respectively.

4. Discussion

The results obtained at the Zacatín rock shelter enable us to examine the exploitation of the coastal area during the Mesolithic–Neolithic transition from three complementary perspectives: the temporal organisation of gathering activities; the management of the intertidal zone, as inferred from the composition and quantitative evolution of the malacological assemblages; and the potential impact of shellfish gathering on the exploited populations, as assessed using biometric parameters. By integrating isotopic analyses with quantitative data (NISP and

MNI), diversity indices and biometric measurements, it becomes possible to assess not only changes in the timing of collection, taxonomic selection, or shell size, but also the broader organisation and intensity of intertidal resource exploitation through time.

4.1. Seasonal dynamics and variability in malacological assemblages

Marine molluscs constitute a significant component of the faunal remains at Zacatín rock shelter. A total of 6,265 remains have been recorded, providing an MNI of 4,066 specimens (Aguirre-Uribesalgo, 2024). The diachronic distribution reveals a peak in Phase 2 (NISP = 2,595; MNI = 1,726), contrasting with Phases 1 (NISP = 1,953; MNI = 1,207) and 3 (NISP = 1,720; MNI = 1,133). However, these differences cannot be explained by the volume of sediment excavated (Table S3), since the phase with the greatest amount (Phase 3: 7.9 dm³) does not yield the greatest number of remains. Furthermore, the relationship between MNI and volume is weak ($R^2 = 0.128$; $p = 0.766$). In terms of depositional rate (Jerardino, 2016), Phases 2 and 3 (3.53 and 1.98 MNI/

year, respectively) show higher values than Phase 1 (0.92 MNI/year). This pattern indicates a higher intensity of shell midden accumulation during Neolithic phases.

From a taxonomic perspective, the quantitative data reveal a trend towards greater concentration within a few taxa (Aguirre-Uribesalgo, 2024). The number of species decreases from 25 in Phase 1 to 21 in Phase 2 and then to 19 in Phase 3. Conversely, dominance increases (Simpson D: 0.611 $\rightarrow$ 0.735 $\rightarrow$ 0.846), as do effective diversity (1/D: 1.637 $\rightarrow$ 1.361 $\rightarrow$ 1.181; $^{\circ}$ D: 2.626 $\rightarrow$ 1.886 $\rightarrow$ 1.562) and equity (H': 0.966 $\rightarrow$ 0.635 $\rightarrow$ 0.446; J': 0.317 $\rightarrow$ 0.224 $\rightarrow$ 0.165). This indicates that an increasing proportion of the total is accounted for by a decreasing number of species.

This trend is clearly reflected in the composition of the assemblage. Gastropods predominate throughout the sequence, increasing progressively from 83.26 % of the MNI in Phase 1 to 89.57 % in Phase 2 and 98.23 % in Phase 3. Conversely, the percentage of bivalves decreases from 16.74 % to 10.43 % and then to just 1.77 %. Within the gastropods, the genus *Patella* is highly represented, increasing in relative weight from 77.38 % to 85.05 % to 91.87 %. In contrast, the percentage of mussels declines significantly: *Mytilus* falls from 10.94 % to 9.15 % to 1.41 %, and *Perna perna* from 3.89 % to 1.16 % to 0.18 %. These changes reflect a marked shift towards exploiting limpets.

At the species level, internal adjustments can also be observed. *P. rustica* increased its representation from 22.45 % to 29.30 %, *P. ulyssiponensis* decreased from 18.64 % to 9.89 %, and *P. caerulea* increased from 12.92 % to 16.33 % during the Neolithic period compared to the Mesolithic period. Taken together, these data suggest a shift towards a smaller number of rocky intertidal species.

The increasing dominance of limpets through time, despite the persistence of a stable harvesting season, suggests that the main changes affected the selection of taxa rather than the temporal organisation of coastal exploitation. This pattern may reflect a combination of environmental and socio-economic factors associated with the Mesolithic–Neolithic transition in the Alboran Sea region. Holocene environmental changes, including sea-level rise and modifications in coastal morphology and marine productivity, may have influenced the availability and distribution of intertidal resources (e.g., Jiménez-Espejo et al., 2008; Jordá et al., 2011). At the same time, the adoption of domesticated animals and the development of agro-pastoral economies likely altered the organisation of subsistence activities and the rhythms of interaction with coastal environments, potentially favouring more selective exploitation strategies focused on abundant and predictable rocky intertidal taxa such as limpets. In this context, the reduction in mussels observed in the assemblage may reflect local ecological conditions or specific harvesting choices, even though broader regional syntheses suggest that bivalves tend to increase in southern Iberian sites after the Last Glacial Maximum (Aura et al., 2002; 2009; 2010, 2016; Jordá Pardo et al., 2016).

Similar trends towards a greater concentration on a limited number of species have been documented in several Neolithic coastal contexts of the Iberian Peninsula (Pascual-Benito, 2014). Limpets also offer higher meat yields than genus such as *Phorcus* (García-Escárcaga and Gutiérrez-Zugasti, 2021) and are similarly documented as dominant elements of shell assemblages in the central Mediterranean (Colonese et al., 2011). The seasonal pattern observed at Zacatín also provides additional insight into these dynamics. Shellfish gathering was already predominantly concentrated during the colder months in the Mesolithic, although collection events occurred throughout the year. During the Early Neolithic, harvesting appears to remain predominantly focused on autumn and winter. No spring-collected specimens were identified in the analysed sample; however, given the limited number of individuals available for each phase, this pattern should be interpreted cautiously. Nevertheless, further analyses including a larger number of specimens from the same taxon, as well as other exploited species, will be necessary to more accurately assess the seasonal patterns developed by these communities. One possible explanation is that the emergence of agro-

pastoral economies led to a partial reorganisation of seasonal activities, with agricultural and herding tasks requiring greater labour investment during spring and summer and potentially reducing the time available for coastal foraging during these periods. Alternatively, the persistence of a cold-season focus may reflect longer-term ecological or cultural patterns already established among Mesolithic coastal populations and subsequently integrated into Neolithic subsistence systems. In this sense, coastal resource exploitation appears to have maintained a stable temporal position within the annual cycle of activities, while the main changes affected the selection and relative importance of the taxa exploited.

4.2. Shellfish gathering seasonality and subsistence strategies

The exploitation of *P. caerulea* at Zacatín rock shelter is significant when compared with other animal resources. This comparison enables us to evaluate whether the collection of molluscs followed its own dynamics or was integrated within a broader subsistence system (Martínez Sánchez et al., 2024). Furthermore, this comparative approach helps us to determine whether the isotopic signal reflects periods of site occupation, or specific decisions regarding resource exploitation within a more complex economic framework.

During Phase 1 (Mesolithic), the seasonality inferred from the collection of molluscs, with a clear emphasis on the colder months, contrasts with the signal provided by the ichthyofauna. Fishing shows a combination of species that can potentially be caught throughout the year, such as sedentary species, and migratory pelagic species, such as sardines and mackerel, whose presence is linked to their seasonal approach to the coast. Among the species identified are *Sardina pilchardus* (Walbaum, 1792) and *Scomber colias* Gmelin, 1789, which are most accessible along the western Mediterranean coast, mainly between spring and late summer (approximately April–September), coinciding with their coastal movements. The identification of small grey mullet, primarily documented in spring and summer, provides an independent seasonal indicator, suggesting that fishing activities were concentrated during the warmer months. The specimens assigned to the *Mugilidae* family, probably *Chelon labrosus* (Risso, 1827) and/or *Mugil cephalus* Linnaeus, 1758, are small-sized individuals, which is consistent with catches in estuaries and shallow areas between May and August, when juveniles approach the coastline. These contrasting records suggest that mollusc collection and fishing did not necessarily follow the same calendar, but rather formed part of complementary strategies distributed throughout the year. Therefore, the seasonal divergence between winter shellfish gathering and summer fishing suggests staggered annual planning, whereby different resources were exploited according to their availability and profitability, reducing dependence on a single biotope.

At the same time, continental resources during the Mesolithic show reduced diversity. The only terrestrial vertebrate identified is the rabbit (*Oryctolagus cuniculus* Linnaeus, 1758), while terrestrial molluscs, dominated by *Iberus alonensis* (Férussac, 1821), constitute the main non-marine resource. The predominance of adult *Iberus alonensis* individuals with diameters > 25 mm suggests a preference for specimens with a higher meat yield. The abundance of this gastropod, together with evidence of size-based selection, indicates that its capture was systematic. However, the lack of direct seasonal markers for these continental resources makes it impossible to establish precise correspondence with the isotopic pattern.

In Phase 2 (Early Neolithic 1), despite the introduction of pottery and the presence of domestic animals, the recorded seasonal pattern shows no significant changes. The documented caprines include remains attributable to sheep and goat, although they occur at low frequencies compared to the total faunal assemblage. Fishing is still evident through a taxonomically diverse set, albeit smaller than in the Mesolithic period, with no clear indications of changes in its temporal organisation. The persistence of migratory species suggests that summer catches still play a key role in the local economy. *S. pilchardus*, *S. colias* and *Mugilidae* are

present, maintaining a catch spectrum that covers at least the spring and summer months. Consequently, the winter isotopic signal recorded in molluscs cannot be interpreted as reflecting exclusively seasonal occupation of the shelter, but rather the selection of specific collection periods within a broader annual cycle of activities.

Phase 3 (Early Neolithic 2) shows a clear increase in the importance of sheep and goats. The presence of domestic caprines, together with other evidence reported by Martínez-Sánchez et al. (2024), suggests an increasing role of livestock-related practices during this phase. Considering the partial preservation of the original shelter structure, the available archaeological record does not allow the precise spatial organisation of these activities to be reconstructed, although the site may have been involved in livestock management practices. Nevertheless, the isotopic pattern indicates that mollusc gathering continued during the colder months. Although there is less evidence for fishing, it did not disappear, which reinforces the idea that coastal activities remained integrated into the site's economy even as livestock practices became more significant.

Comparing the different animal resources with the isotopic signal suggests that the seasonality observed in molluscs does not reflect limited occupation of the shelter, but rather a recurring preference for collecting shellfish during the colder months. This practice coexisted with activities carried out at other times of the year, such as fishing for migratory and sedentary species, and exploiting continental resources. This complementarity indicates that shellfish collection played a consistent role in the exploitation of diverse resources throughout the annual cycle during the Mesolithic–Neolithic transition.

4.3. Shell size variability and potential harvesting pressure

Decreases in shell size have often been interpreted as an indicator of increasing harvesting pressure on mollusc populations in archaeological contexts along the Atlantic façade of Europe (Álvarez-Fernández et al., 2011; Arniz-Mateos et al., 2024; Gutiérrez-Zugasti, 2011; García-Escárcaga et al., 2022). In this context, the biometry of *Patella* provides an independent means of assessing whether the changes documented in mollusc exploitation across the sequence, particularly the increasing concentration in *Patella* and the decline in diversity in Phase 3, could have been accompanied by increasing pressure on the resource.

The analysis of *P. caerulea*, the species used for the isotopic reconstruction, shows no statistically significant reduction in shell size across the sequence. Mean shell length decreased slightly from Phase 1 (27.75 mm) to Phase 2 (27.47 mm) and Phase 3 (26.60 mm), but these were not significant ($p > 0.05$). The dispersion pattern nevertheless suggests some changes in group composition. In *P. caerulea*, Phase 1 shows greater variability (SD 6.15) and a wider size range (28.71 mm), whereas Phases 2 and 3 display slightly lower variability and a more homogeneous distribution (see Table 3). Although this pattern is less clear in the other species, the overall stability of median and mean values suggests that these differences may reflect variations in size selection or the repeated exploitation of similar coastal sectors rather than increasing harvesting pressure.

The biometric patterns observed in the other two *Patella* species broadly support this interpretation. In *P. ulyssiponensis*, mean shell length decreases slightly between Phase 1 (26.18 mm) and Phase 2 (25.46 mm) but returns almost to the initial value in Phase 3 (26.15 mm). Similarly, in *P. rustica*, shell size remains remarkably stable throughout the sequence, with mean lengths of 23.74 mm (Phase 1), 23.73 mm (Phase 2) and 24.00 mm (Phase 3). In both species, the Kruskal–Wallis test indicates no significant differences between phases ($p > 0.05$), and the dispersion patterns do not support a simple scenario in which intensification would lead to a progressive reduction in shell size.

The integration with the isotopic results reinforces this interpretation. The $\delta^{18}\text{O}$ signal in *P. caerulea* indicates a repeated predominance of harvesting during the colder months across all three phases, suggesting a

consistent seasonal pattern despite changes in assemblage composition and an increased concentration of *Patella* throughout the sequence. If the intensification of shellfish collection had resulted in significant selective pressure on the exploited populations, a clearer trend towards smaller shell sizes would be expected, particularly in phases with higher densities of remains and greater taxonomic dominance (e.g., Colonese et al., 2018). However, the absence of significant differences in maximum shell length across the three species, together with the overall stability of mean values, suggests that there is no clear signal of increased harvesting intensity affecting intertidal resources through a generalised decrease in shell size, at least at the temporal and sample scale considered here. This does not imply an absence of changes in shellfish harvesting practices. Rather, such changes appear to be more clearly reflected in other parameters, such as species diversity, deposition ratio of remains and degree of specialisation, than in shell size patterns.

The integration of isotopic, taxonomic, biometric and faunal data suggests that the changes documented at Zacatín mainly concern the intensity of mollusc exploitation. The $\delta^{18}\text{O}$ analysis of *P. caerulea* indicates recurrent harvesting dominated by the colder months in all three phases, although the signal is broader during the Mesolithic and becomes more seasonally concentrated in the Neolithic. This pattern persists despite the progressive reduction in taxonomic diversity, the increasing dominance of *Patella*, and variations in density and MNI, particularly evident in Phase 2. At the same time, biometric data show no significant decrease in shell size nor diachronic trends indicating increasing pressure on the exploited populations. Coastal exploitation therefore appears to have been reorganised around a stronger focus on specific taxa without substantially altering the harvesting calendar.

When the full range of animal resources is considered, fishing provides complementary seasonal signals, while continental resources become more prominent during the Neolithic phases (Martínez Sánchez et al., 2024). Nevertheless, the contribution of domestic fauna at the shelter remains limited. In this context, the absence of major changes in the seasonality of marine resource procurement may be related to the still secondary role of agro-pastoral resources at Zacatín, where coastal exploitation continued to occupy an important position within the annual cycle of activities.

4.4. Seasonality of shellfish harvesting in regional and environmental context

The pattern observed at Zacatín does not seem exceptional but instead finds clear parallels in numerous sites along both the European Atlantic facade and the Mediterranean basin, where shell isotopic analyses have revealed a recurrent preference for procurement during the colder months in both hunter-gatherer and early food-producing contexts (Arniz-Mateos et al., 2026; Bosch et al., 2018; Colonese et al., 2018; Marchán-Fernández et al., 2025; Mannino et al. 2003; Mannino et al., 2011; García-Escárcaga et al., 2019; 2024a; 2024b; 2025; Prendergast et al., 2016; Yanes et al., 2018). Episodes of intensified summer shellfish consumption remain comparatively rare and episodic (Branscombe et al., 2020).

Several studies examining the effects of the adoption of food-producing economies on the seasonality of intertidal resource exploitation highlight a notable degree of continuity. Isotopic records from Ksar 'Akil, Haua Fteah and Ifri Oudadane indicate that seasonal patterns of mollusc procurement remained relatively stable throughout the neolithisation process (Bosch et al., 2018; Prendergast et al., 2016; Yanes et al., 2018), closely matching the evidence documented at Zacatín.

The repeated winter bias nevertheless invites consideration of potential explanatory factors. It has been proposed that some intertidal gastropods may provide higher energetic returns during colder months due to gametogenic development, which can result in increased mollusc meat yield and lipid content (Cumplido et al., 2020; García-Escárcaga et al., 2019; 2024b; Kapranova et al., 2019). In addition, lower

temperatures could favour the preservation of collected resources by slowing decomposition processes, while the risk of intoxication associated with harmful algal blooms, more frequent in warmer periods, is reduced (García-Escárczaga et al., in review). Regardless of which of these factors may have been most influential, the key observation at Zacatín is that this winter-oriented procurement strategy persists despite the introduction of agro-pastoral economies.

While the harvesting calendar remains stable, changes in shell assemblage composition may be contextualised within broader Holocene coastal transformations. During the last eustatic phase, sea-level rise associated with global climatic warming and partial melting of polar ice sheets (Ruddiman and McIntyre, 1981) produced significant modifications along the Iberian coastline (García-Artola et al., 2018). The progressive loss of coastal plains and the reconfiguration of certain lagoonal systems into more exposed rocky shorelines may have altered the relative availability of intertidal resources, thereby influencing the taxonomic composition of exploited assemblages (Fernández-López de Pablo and Gabriel 2016; Brisset et al., 2022). In Mediterranean settings, the consolidation of these geomorphological transformations is generally dated to around 7000–6000 cal BP (c. 5000–4000 cal BC) (Leorri et al., 2012; Brisset et al., 2022), a chronological framework consistent with the increased representation of rocky intertidal taxa during Neolithic phases.

The introduction of domesticated species at the onset of the Neolithic may have contributed to reorganising the economic role of coastal resources without necessarily modifying the seasonal harvesting calendar. At Zacatín, Early Neolithic levels already document livestock husbandry involving domestic taxa, alongside the presence of wheat remains whose specific varieties remain undetermined (Martínez Sánchez et al., 2024). The still limited contribution of agro-pastoral resources in the faunal and archaeobotanical assemblages is consistent with the persistence of coastal subsistence practices and with the absence of a substantial seasonal “reprogramming” of shellfish procurement, even as broader changes in terrestrial fauna and site function become apparent.

Overall, the Zacatín sequence aligns with regional and Mediterranean archaeological evidence pointing to a marked continuity in the seasonality of shellfish exploitation throughout the process of neolithisation (Bosch et al., 2018; Colonese et al., 2011; Prendergast et al., 2016; Mannino et al., 2011; Colonese et al., 2018; Yanes et al., 2018). These results suggest that early Holocene environmental changes and economic developments are primarily expressed through taxonomic selectivity, while the seasonal scheduling of mollusc harvesting remained a stable component of the annual subsistence cycle.

5. Conclusion

The Zacatín sequence suggests that Neolithisation along the Alboran Sea littoral did not lead to the abandonment or seasonal reorganisation of shellfish gathering, but rather to a redefinition of its role within an increasingly diversified economic strategy. The persistence of a cold-season bias in *P. caerulea* suggests that shellfish procurement may reflect recurrent decisions consistent with annual planning, in which the intertidal zone functioned as a stable component of the seasonal calendar, while other activities (e.g., fishing of migratory species or the exploitation of continental resources) were scheduled at different times of the year.

At the same time, the progressive taxonomic concentration on *Patella* and the decline of bivalves point to a shift in the logic of coastal resource management: rather than broadening the exploited spectrum, taxa from rocky intertidal environments were prioritised, consistent with more selective harvesting strategies. This adjustment may be interpreted as a combined response to Holocene environmental conditions (reconfiguration of coastal fronts and changes in the relative availability of biotopes) and to the territorial reorganisation associated with the adoption of agro-pastoral practices, without implying a detectable increase in pressure on the exploited populations.

More broadly, Zacatín fits well within the Mediterranean pattern of persistent shellfish exploitation throughout the process of neolithisation. This reinforces the view of a non-linear transition, in which the adoption of domesticates coexisted with well-established coastal economies and where shellfish gathering functioned as a stable and predictable resource within increasingly complex annual subsistence schedules.

CRediT authorship contribution statement

A. Aguirre-Urribesalgo: Formal analysis, Data curation, Conceptualization. **A. García-Escárczaga:** Methodology, Investigation, Data curation, Conceptualization. **R.M. Martínez-Sánchez:** Investigation, Data curation, Conceptualization. **A.C. Colonese:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Álvarez-Fernández:** Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Saña-Seguí:** Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2026.105957>.

Data availability

Data will be made available on request.

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