



# Environmental Archaeology

The Journal of Human Palaeoecology

ISSN: 1461-4103 (Print) 1749-6314 (Online) Journal homepage: [www.tandfonline.com/journals/yenv20](http://www.tandfonline.com/journals/yenv20)

## Seasonality from Mg/Ca Ratios of Prehistoric Shellfish Exploitation (*Patella caerulea* Linnaeus, 1758) at the Haua Fteah (Libya, North Africa)

Rosa Arniz-Mateos, Chris O. Hunt, Graeme Barker & Niklas Hausmann

To cite this article: Rosa Arniz-Mateos, Chris O. Hunt, Graeme Barker & Niklas Hausmann (07 Mar 2026): Seasonality from Mg/Ca Ratios of Prehistoric Shellfish Exploitation (*Patella caerulea* Linnaeus, 1758) at the Haua Fteah (Libya, North Africa), Environmental Archaeology, DOI: [10.1080/14614103.2026.2639149](https://doi.org/10.1080/14614103.2026.2639149)

To link to this article: <https://doi.org/10.1080/14614103.2026.2639149>



© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



[View supplementary material](#)



Published online: 07 Mar 2026.



[Submit your article to this journal](#)



Article views: 7



[View related articles](#)



[View Crossmark data](#)

## Seasonality from Mg/Ca Ratios of Prehistoric Shellfish Exploitation (*Patella caerulea* Linnaeus, 1758) at the Haua Fteah (Libya, North Africa)

Rosa Arniz-Mateos <sup>a</sup>, Chris O. Hunt <sup>b</sup>, Graeme Barker <sup>c</sup> and Niklas Hausmann <sup>a</sup>

<sup>a</sup>Leibniz Zentrum für Archäologie (LEIZA), Mainz, Germany; <sup>b</sup>School of Biological & Environmental Sciences, Liverpool John Moores University, Liverpool, UK; <sup>c</sup>McDonald Institute for Archaeological Research, University of Cambridge, Cambridge, UK

### ABSTRACT

Mollusc shells, commonly preserved in archaeological records worldwide, capture high-resolution, sub-annual environmental information at local scales through the incorporation of chemical elements during their formation. These geochemical signals can be used to infer the season of shellfish collection by past human populations. This study presents new seasonal data derived from magnesium-to-calcium (Mg/Ca) ratios in *Patella caerulea* Linnaeus, 1758 from the archaeological site of Haua Fteah in northern Cyrenaica (Libya, North Africa). Our data were obtained through elemental mapping using laser induced breakdown spectroscopy (LIBS), which enables the visualisation of intra-shell geochemical variation at high spatial resolution. The results provide detailed reconstructions of shellfish collection seasonality from the Capsian to the Neolithic periods, covering a ~5,000 year span from the latest Pleistocene through the Early-Mid Holocene. We demonstrate that mollusc gathering occurred throughout the year, with a higher frequency in the autumn and winter seasons, suggesting that marine resource use was more consistent than previously assumed. We compare our data with previous seasonality studies of different mollusc species to demonstrate that seasonal collection patterns varied between mollusc species, suggesting differences in marine exploitation subsistence strategies, probably related to the availability of other food resources, energetic return and mollusc processing techniques.

### ARTICLE HISTORY

Received 12 December 2025  
Revised 20 February 2026  
Accepted 24 February 2026

### KEYWORDS



LIBS; Elemental analysis;  
Mollusc shells;  
Mediterranean; Seasonality;  
Subsistence strategies

## Introduction

Archaeological research has shown that marine mollusc shells are documented in Mediterranean sites from the Lower Palaeolithic, with an increasing presence during the Middle and Upper Palaeolithic and a consistent record in the Holocene (Colonese et al. 2011; Stringer et al. 2008; Verdún-Castelló and i Bernad 2020; Zilhão et al. 2010). This long practice of collection underlines their role as a consistent dietary resource. As such they are a key asset for reconstructing patterns of seasonal exploitation for human consumption. From a dietary perspective, molluscs offered clear advantages: they supplied high-quality protein (Erlandson 1988) and also contributed essential fatty acids such as arachidonic acid (AA) and docosahexaenoic acid (DHA), nutrients that are fundamental for human growth and brain function (Broadhurst et al. 2002; Carlson and Kingston 2007). Despite these benefits, the role of marine resources in prehistoric Mediterranean subsistence, and molluscs in particular, has received comparatively less attention than in Atlantic contexts (Colonese et al. 2011; Gutiérrez-Zugasti et al. 2011). One of the

possible reasons is the apparent absence of large shell middens along Mediterranean coasts, such as those found in oceanic regions (Bailey and Flemming 2008). Nevertheless, over the past decades, several studies have evaluated the contribution of molluscs, demonstrating the antiquity of their exploitation and their potential as key resources for human consumption (e.g. Bailey and Milner 2002).

The seasonality of mollusc collection is an important aspect when evaluating and understanding their role in human subsistence strategies and settlement patterns (Andrus 2011; Thomas 2015). The application of spectroscopic techniques to mollusc shells and their reliability as proxies to reconstruct paleoenvironmental conditions and the season of shell collection has been studied over the past decades (Fenger et al. 2007; Ferguson et al. 2011; Freitas et al. 2005; Graniero et al. 2017; Wanamaker et al. 2008). In this context, laser induced breakdown spectroscopy (LIBS) technique allows for the quantitative determination of magnesium to calcium (Mg/Ca) intensity ratios, which are strongly temperature dependent during carbonate precipitation (Schweikhardt et al. 2011). Trace

**CONTACT** Rosa Arniz-Mateos  rosa.arnizmateos@leiza.de  Leibniz Zentrum für Archäologie (LEIZA), Mainz, Rhineland-Palatinate 55116, Germany  
 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/14614103.2026.2639149>.

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group  
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

element analysis, particularly Mg/Ca ratios in *Patella* spp., has shown strong correlations with instrumental seawater temperatures (García-Escárczaga et al. 2015, 2018; Hausmann et al. 2017, 2019, 2024; Mirapeix et al., 2025a). In the case of the Haua Fteah cave (Cyrenaica, Libya), which is the focus of this study, previous studies have tested the potential of Mg/Ca intensity ratios of shell calcium carbonate from modern specimens of *Patella caerulea* Linnaeus, 1758 collected near the town of Sousa 10 km to the west (Hausmann et al. 2019; Theodoraki et al. 2026). These studies show a high correlation between instrumental and reconstructed seawater temperatures, confirming their potential for reconstructing past environmental conditions and determining shellfish collection seasonality.

Past seasonality studies of the marine gastropod *Phorcus turbinatus* (Born, 1778), previously referred by the genus names *Monodonta* or *Osilinus*, have been carried out from several archaeological sites across the central and eastern Mediterranean, including Grotta dell'Uzzo (Mannino et al. 2007), Grotta della Serratura (Colonese et al. 2009), Grotta d'Oriente (Colonese et al. 2009, 2018) and Cala Mancina in Italy (Colonese et al. 2009), as well as in Vela Spila in Croatia (Branscombe, Bosch and Miracle 2021), Franchthi Cave in Greece (Deith and Shackleton 1988) and the Haua Fteah (Prendergast et al. 2016a). However, despite the abundant presence of *Patella* spp. in Mediterranean archaeological contexts (Bosch et al. 2015; Colonese et al. 2011; Hunt et al. 2011; Verdún-Castelló and i Bernad 2020), few seasonality studies of this mollusc have been published. Although previous seasonality studies of *P. turbinatus* have contributed significantly to our understanding of shellfish exploitation at the Haua Fteah (Hunt et al. 2011; Prendergast et al. 2016a, 2016b), the interpretation of these results has been limited by small sample sizes and individual mollusc taxa that may not be representative of wider patterns of mollusc collection seasonality.

In this study, we present a new and extended seasonality dataset from Mg/Ca ratios of *P. caerulea* from the Haua Fteah. These results allow us to have an improved reconstruction of the seasonal strategies employed by human groups that occupied the site during the terminal Late Glacial and Early-Mid Holocene and provide a more detailed interpretation of seasonal coastal subsistence strategies and settlement patterns in the central and eastern Mediterranean basin.

## Background

### The Haua Fteah Site Background

The Haua Fteah cave is located in Cyrenaica, north-eastern Libya, at the foot of the northern escarpment of the Gebel Akhdar massif, approximately 1 km

inland from the Mediterranean coast and at an elevation of 73 m above sea level (Figure 1) (Douka et al. 2014; Hunt et al. 2010). Its geomorphological position, combining proximity to the Mediterranean and the ecologically diverse Gebel Akhdar massif, provided favourable conditions for long-term human settlement, potentially serving as a refugium during climatically unstable periods (Barker et al. 2010, 2012; Barker and Hunt 2025; Prendergast et al. 2016a).

The cave was first systematically investigated by Charles McBurney in the 1950s, whose excavations revealed a 14 m stratigraphic sequence documenting one of the most extensive records of human occupation in North Africa (Hunt et al. 2010; McBurney 1967). More recently, the Cyrenaican Prehistory Project (CPP) (2007–2015) expanded this work with new excavations and dating programs, refining the chronology and cultural attributions of the deposits (Barker et al. 2008, 2009, 2010, 2012). The McBurney excavations revealed a sequence of seven major cultural phases that he suggested spanned the past 80,000 years. The CPP excavations have confirmed the cultural sequence but also shown that the human use of the cave began much earlier, around 140,000 years ago (Barker et al. 2012; Douka et al. 2014; Jacobs et al. 2017). The seven phases and their currently agreed chronology are: Pre-Aurignacian (Middle Palaeolithic in McBurney's terminology, or Middle Stone Age) dated to ca. 140–80 ka cal. BP; Levallois-Mousterian (MSA) between 80 and 45 ka cal. BP; Dabban (Upper Palaeolithic, or LSA in African terminology), extending from ca. 45 to 19 ka cal. BP; Eastern Oranian (LSA Epipalaeolithic) between 15.5 and 12.2 ka cal. BP; Capsian (LSA Mesolithic) from 12.2 to 8.5 ka cal. BP; Neolithic of Capsian Tradition (so-called because of the many similarities in material culture with that of the Capsian, but hereafter referred to for simplicity as Neolithic), 8–3.5 ka cal. BP; and, finally, deposits of the Graeco-Roman and Historic periods from ca. 2.5 ka cal. BP to the present (Barker et al. 2012).

Subsistence evidence includes a broad spectrum of resources, ranging from large and small mammals to reptiles, birds, wild plants, and both terrestrial and marine molluscs (Barker et al. 2010, 2012; Klein and Scott 1986; McBurney 1967). Marine molluscs are present throughout much of the Late Pleistocene and Early-Middle Holocene sequence, with *P. turbinatus* and *P. caerulea* particularly abundant in Epipalaeolithic (Oranian), Mesolithic (Capsian) and Neolithic contexts (Hunt et al. 2011; Prendergast et al. 2016a). Their distribution, together with faunal remains of mammals, birds, and reptiles, provides evidence for broad-spectrum subsistence strategies and for shifting patterns of seasonality in resource exploitation, especially during the transition from the Late Glacial to the Early Holocene (Barker et al. 2010, 2012; Klein and Scott 1986; McBurney 1967).



**Figure 1.** Location of the Haua Fteah and Sousa in Cyrenaica, northeastern Libya, at the foot of the Gebel Akhdar massif. Contours in metres above sea level.

### Past Work on Seasonality at the Haua Fteah

Shell remains provide valuable information on how coastal resources were integrated into human subsistence strategies (Colonese et al. 2011; Mannino et al. 2011; Milner 2009). The presence of marine molluscs, particularly *P. turbinatus* and *P. caerulea*, is well documented throughout the Capsian and Neolithic sequences at the Haua Fteah (Emiliani and Mayeda 1964; Hunt et al. 2011; Klein and Scott 1986). Previous studies identified changes in the seasonality of *P. turbinatus* collection through the Late Pleistocene to Early Holocene sequence of the cave, reflecting different patterns in resource use. During the Capsian (12.2–8.5 ka cal. BP), *P. turbinatus* reflected a restricted pattern of collection, concentrated in winter and, to a lesser extent, in summer (Prendergast et al. 2016a). In the Neolithic (8–3.5 ka cal. BP), collection also occurred mainly in winter, with a smaller representation in autumn (Prendergast et al. 2016a).

Other faunal and botanical resources, including fish and crabs, *Ammotragus lervia* (Pallas, 1777) (Barbary sheep or aoudad), *Bos* sp., gazelle, hartebeest, and birds, were also exploited throughout the year (Barker et al. 2010; MacDonald 1987). In the case of *A. lervia*, hunting took place throughout the year, with a slight emphasis on the summer and autumn seasons, particularly during the Capsian period (Wall-Scheffler

2007). The ecological behaviour of *A. lervia* and *Bos* sp. reflects a limited seasonal mobility, rarely undertaking long-distance migrations (Ciuti et al. 2009; Hampy 1978). Consequently, their diet primarily reflects the composition of local vegetation. Isotopic evidence from *A. lervia* and *Bos* sp. suggests that these herbivores primarily consumed C3 plants during the Oranian, consistent with the predominance of cooler and humid environmental conditions (Reade et al. 2016). Later, during the Neolithic, C4 plants were incorporated into the diets of local herbivores, *A. lervia* and *Bos* sp. (Reade et al. 2016), in a period of increased aridity around 8–7.3 ka cal. BP (Prendergast et al. 2016b).

Plants were also eaten: cones of *Pinus halepensis* were collected in summer and processed by fire (Prendergast et al. 2016a), while wild legumes, juniper (*Juniperus phoenicea*), lentisk (*Pistacia lentiscus*), and myrtle (*Myrtus communis*) were also collected in summer (Barker et al. 2010).

## Materials and Methods

### Materials

In this investigation, 140 shells of *P. caerulea* were analysed through Mg/Ca imaging (Table 1). The shell assemblage was limited by the species available from McBurney's excavations, and from the CPP

**Table 1.** Provenance of the material analysed in this study. See text for explanation of phasing.

Culture	Modelled age (ka cal. BP)	CPP phase	McBurney spit	CPP Context	Number of specimens
Early Capsian	12.2–11.2	MT-10	XI	–	14
			78	–	8
Capsian	11.2–8.5	MT-11	X	–	26
			UT-1	135	3
Neolithic	8–5.5	UT-2	IX	–	22
			IX – VIII	–	12
			VIII – VI	–	5
			VII	–	29
			IX-VII	133	3
				132	5
	131	7			
	130	6			

project excavations, as well as by the preservation of the material. McBurney's material was accessed with permission from the Museum of Archaeology and Anthropology, University of Cambridge.

### Excavation and Sampling Methods

The first group of shells was collected by McBurney during his three excavation seasons (1951, 1952, 1955). He mostly used hand recovery methods (trowelling) and dry sieving, especially in the second and third seasons, while the first season involved some pick-and-shovel digging to ascertain the depth of the archaeological deposits. He maintained rigorous recording practices and demonstrated a strong understanding of the site stratigraphy, which is reflected in the clear lithological changes he distinguished (McBurney 1967). His sieving appears to have been systematic, ensuring reliable recovery of shell material and was capable of recovering small material, including shell beads made on *Columbella rustica* (Linnaeus, 1758) (~4 mm) (McBurney 1967), although the collections are somewhat biased towards whole and near-whole specimens, with fragmentary material being less frequent than in CPP excavations.

The second group of shells was collected by the CPP team between 2007 and 2013 (with no excavation in 2011), using hand trowelling, with sediments processed by bucket sieving in the first season and a pump-driven flotation machine in later seasons. The CPP project applied a single-context excavation method. All sediments were floated and wet-sieved, recovering all material > 2 mm, including shells, which were then completely hand-sorted. Two ~30 × 30 cm sample columns were excavated along the western side of the Upper Trench, and a small additional 1 × 1 m trench (Trench U) was excavated in Neolithic layers. This ensured that shells were recovered systematically and representatively across the stratigraphy.

Correlations between McBurney layers and CPP contexts were established by Dr Lucy Farr, Dr Sacha Jones, Dr Evan Hill and Professor Hunt (Barker

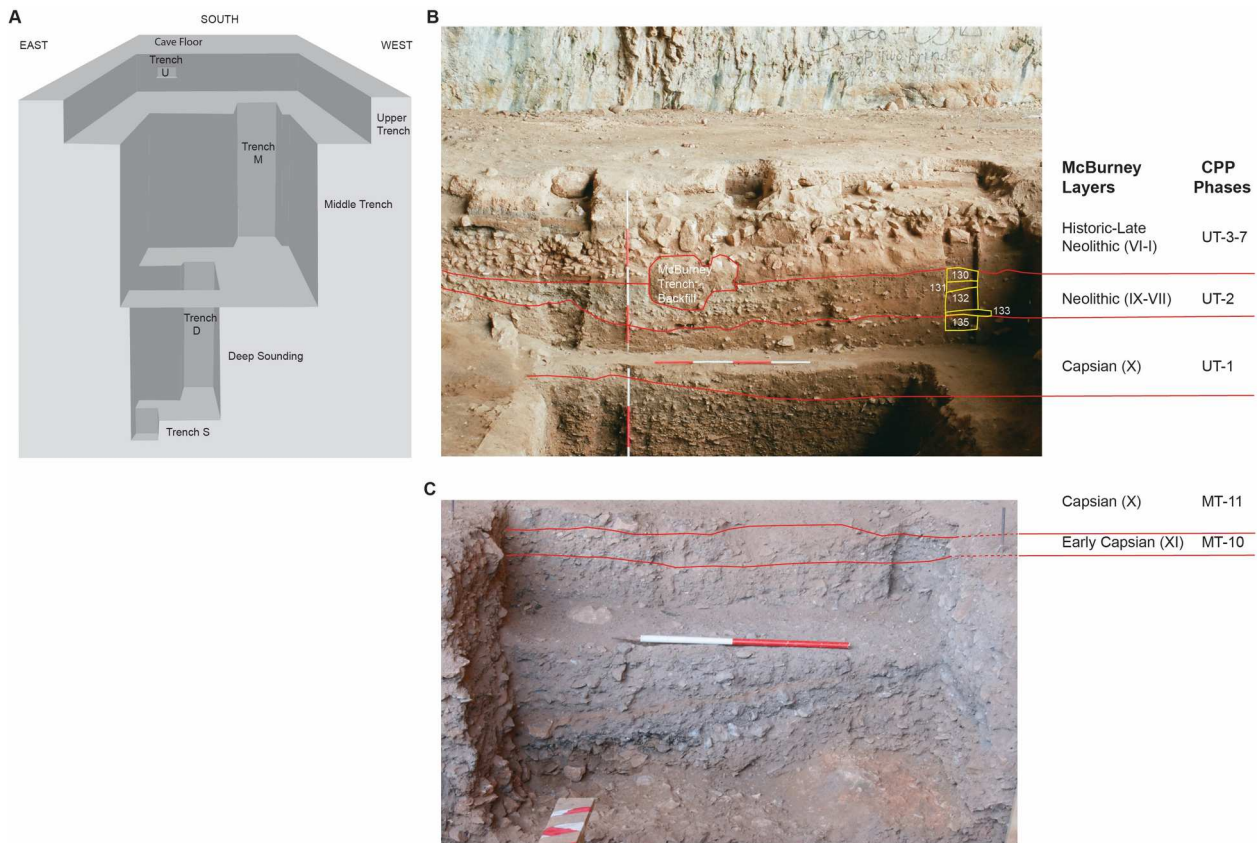
et al. 2008, 2009, 2010, 2012), combining detailed re-study and geochemical sampling of the cleaned McBurney sections and the 30 × 30 cm sample columns excavated by the CPP team, along with parallel sediment analyses of the Upper and Middle Trench stratigraphies (Inglis 2011).

### Shell Units Analysed

The sequence spans the Capsian (12.2–8.5 ka cal. BP) to the main Neolithic phases (8–5.5 ka cal. BP). The cave deposits present a complex stratigraphy, structured into unconformity-bounded units (Hunt et al. 2011), with the provenance and number of analysed specimens for each stratigraphic unit summarised in Table 1.

By the end of excavation in 1955, the McBurney trench consisted of three units: an Upper Trench measuring 10 m x 10 m x 2 m deep; a Middle Trench (not his terminology) measuring 6 m west/east x 4.5 m north/south by 6.5 m deep; and a Deep Sounding measuring 2.5 m west/east by 2 m north/south by 5 m deep (Figure 2(a)). The CPP excavated c. 2 m x 1 m trenches down the north-facing walls of these trenches, and from these defined a sequence of Upper Trench (UT), Middle Trench (M) and Deep Sounding (DS) stratigraphic units that were correlated where possible with McBurney layers and spits. MT-11 (Table 1), the top CPP unit in the Middle Trench, is stratigraphically equivalent to UT-1, the bottom CPP unit of the Upper Trench. From the Upper Trench, McBurney archive shells were obtained from UT-2 (McBurney spits 7, 6–8, 8–9 and 9), Holocene deposits spanning the main phase of the Neolithic, correlating with McBurney's Layers IX–VI (Hunt et al. 2010).

Additional samples of equivalent age were analysed from CPP UT-2 contexts 130, 131, 132 and 133, mainly from a 30 cm x 30 cm sample column excavated down the western side of the Upper Trench. A further context, CPP 135, assigned to UT-1, is equivalent to McBurney's Layer X and belongs to the Capsian, dated to ca. 11.5–8.5 ka cal. BP. From the Middle Trench, shells were studied from two contexts:



**Figure 2.** Stratigraphic relationships of the samples analysed in this study. A. Schematic cut-through of the excavations in the Haua Fteah showing the McBurney Upper Trench, Middle Trench and Deep Sounding and the location of the Cyrenaica Prehistory Project sample trenches U, M, D and S on their southern side (after a drawing by Dr Evan Hill). B. The western side of the McBurney Upper Trench and the top of his Middle Trench showing the location of his layers and sampling by the Cyrenaica Prehistory Project used in this study. Context 135 is in CPP stratigraphic unit UT-1 and Contexts 133–130 are in stratigraphic unit UT-2. C. The top of CPP Trench M on the south side of the McBurney Middle Trench, seen from the north, showing the CPP stratigraphic units MT-10 and MT-11 and their respective correlations with McBurney Layers XI and X. In B and C the scales are in 0.5 m divisions and the images are by Graeme Barker.

MT11.1 (McBurney spit 10) and MT10.1 (McBurney spits 11 and 78). These correlate with Capsian Layers XI and X.

Shell selection followed two main criteria. First, only well-preserved specimens were considered, excluding those affected by fragmentation, carbonification or bioerosion (Figure 3). Second, to minimise ontogenetic effects and avoid growth stops, we only selected limpets that were below 45 mm in length for analysis (Prendergast and Schöne 2017) (Supplementary Information 1).

## Methods

### LIBS and Mg/Ca Imaging

Prior to analysis, the shell assemblage was cleaned in water for 48 h to remove adhered sediment and subsequently air-dried at room temperature. Two transverse sections of each specimen, oriented parallel to the maximum growth axis, were obtained using a Qcut 150 A QATM diamond low-speed saw to expose the internal growth layers. Specimens with irregular cuts were polished with metallographic

abrasive paper of decreasing grain size (P800, P1200, P2400) to ensure a flat surface for analysis. Mg/Ca imaging was performed using LIBS which has proven effective in generating high-resolution elemental distributions in biogenic carbonates (García-Escárczaga et al. 2015; Hausmann et al. 2019; Hausmann, Surge, and i Godino 2024; Mirapeix et al. 2025a, 2025b). LIBS is based on the ablation of sample material by a pulsed laser beam, producing a plasma that emits characteristic radiation. The resulting emission lines, recorded by a spectrometer, provide a chemical fingerprint of the sample.

The LIBS setup used in this study consisted of a Litron Nano DPSS 60–100 laser operating at a wavelength of 1064 nm, coupled to an Andor Kymera 193-A spectrometer and an Andor ICCD iStar DH320T-25F-03 detector to enhance signal intensity. The laser beam was delivered through a beam tube into the sample chamber, which contained an XYZ motorised platform for precise positioning (see Hausmann et al. 2023 for further technical specifications). Elemental ratios were calculated using two emission lines: Ca II at 315.887 nm and Mg II at 279.553 nm,



**Figure 3.** Four examples of archaeological specimens of *P. caerulea* analysed in this study. Top view and interior view (from left to right).

selected based on the spectral range of the spectrometer and their relative intensity.

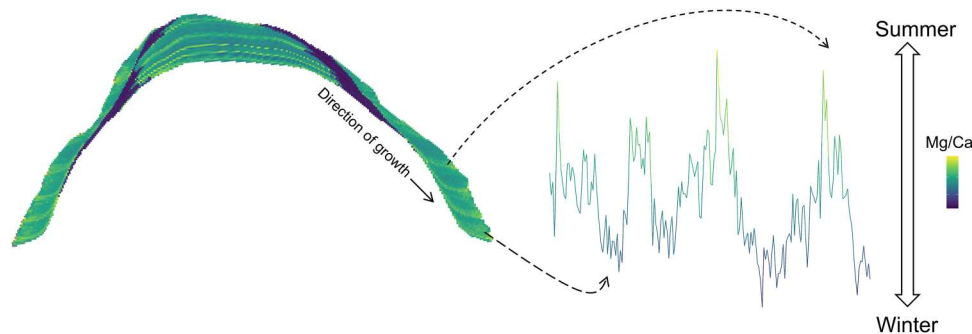
The Mg/Ca imaging strategy combined 2-dimensional imaging of the anterior or posterior (depending on the state of preservation) section of each shell from the edge towards the apex at a 50  $\mu\text{m}$  spatial resolution, either across the whole width or in a 400–800  $\mu\text{m}$  corridor, with complementary linear scans at 30  $\mu\text{m}$  resolution.

Linear scans were taken across the intermediate zone of the M+2 layer and oriented perpendicular to the growth lines. This dual sampling provided a detailed characterisation of intra-shell Mg/Ca variability recorded during shell growth.

#### Season of Collection Estimation

To determine the season of mollusc collection by past human populations at the Haua Fteah, we examined

the cyclical variation in Mg/Ca ratios along the growth axis of limpet shells. Higher Mg incorporation reflects faster crystallization rates at elevated temperatures, thereby enabling reconstruction of sub-annual to annual environmental variability (Cobo et al. 2017). High Mg/Ca values are interpreted as indicative of summer growth, while lower values reflect winter conditions, intermediate values are associated with spring and autumn (see Hausmann et al. 2019, 2024; Theodoraki et al., 2026). These seasonal patterns are visualised in Mg/Ca elemental 2D maps as colour gradients, with summer maxima in yellow-green and winter minima in blue-purple (Figure 4). Line scans provided an additional perspective on seasonal temperature change, but due to intra-increment variability, their annual maxima and minima, as well as the last recorded temperature, do not always reflect the



**Figure 4.** Mg/Ca elemental 2D map and line scan of a limpet section used to determine the season of collection. The map and the line scan show cyclical variation in Mg/Ca ratios along the shell's growth axis, corresponding to seasonal changes in sea surface temperature. Green to yellow colours represent high Mg/Ca values interpreted as summers, while blue tones indicate winters. The final growth increment at the shell edge is related to the season of shell collection.

elemental change across the entire growth increment width. Consequently, we rely primarily on visual assessment of 2D elemental maps, which allow for a more comprehensive evaluation of seasonal variation and the continuity or cessation of growth. The final growth increment at the shell margin is compared against the overall seasonal pattern to infer the season of death, which is assumed to correspond to the season of human collection.

## Results

### Mg/Ca Seasonal Variations

Maps and linear scans for a total of 140 specimens were produced from the archaeological specimens of *P. caerulea* from the Haua Fteah (Supplementary Information 2, which contains the images of the maps, is provided with the article, and the CSV files are available at <https://github.com/Rosarniz/LIBS-imaging-Haua-Fteah>). The Mg/Ca data reveal a consistent pattern of seasonal cyclicality with alternating winter and summer bands that record less than one to two seasonal cycles per year. This cyclic pattern is visible within the calcitic layers of the shell, where Mg/Ca intensity ratios vary between 0.4 and 2. The calcitic winter bands show Mg/Ca intensity ratios of approximately 0.5, whereas the summer bands reach values around 1.5 in the shell assemblage (Figure 5).

### Seasonal Patterns of Collection

The seasonality of collection varied between the Capsian and Neolithic periods (Table 2). For the Early Capsian (12–11.2 ka cal. BP), represented by phase MT-10, limpet collections were predominantly concentrated in winter ( $n = 12$ ), followed by spring ( $n = 5$ ), summer ( $n = 4$ ), and autumn ( $n = 1$ ). During the Capsian (11.5–8.5 ka cal. BP), from the phase MT-11, autumn becomes the most represented season ( $n = 10$ ), followed by winter ( $n = 7$ ), summer ( $n = 5$ ), and spring ( $n = 4$ ). This distribution reflects a broader and more balanced seasonal collection compared to the Early Capsian.

Taking the Capsian as a whole, winter remains the most represented season ( $n = 22$ ), followed by autumn, spring and summer, indicating that limpet exploitation was mainly concentrated during winter and autumn ( $n = 33$ ), but spring and summer are also represented ( $n = 18$ ), suggesting that although human groups preferentially collected limpets during winter and autumn, exploitation was not completely restricted to these months.

During the Neolithic (8–5.5 ka cal. BP), represented by the phase UT-2, an almost identical seasonal collection pattern is visible. Limpet collections were concentrated in winter ( $n = 39$ ), spring ( $n = 14$ ), summer ( $n =$

14) and autumn ( $n = 22$ ). Winter remains generally dominant, particularly in spits 7, 9, CPP contexts 131 and 132. Spit 8–9 and CPP contexts 130 exhibit a more balanced seasonal distribution, with spring or autumn exceeding winter representation, indicating that Capsian and Neolithic groups at the Haua Fteah exploited limpets throughout different parts of the annual cycle, though with a clear winter preference (Figure 6).

## Discussion

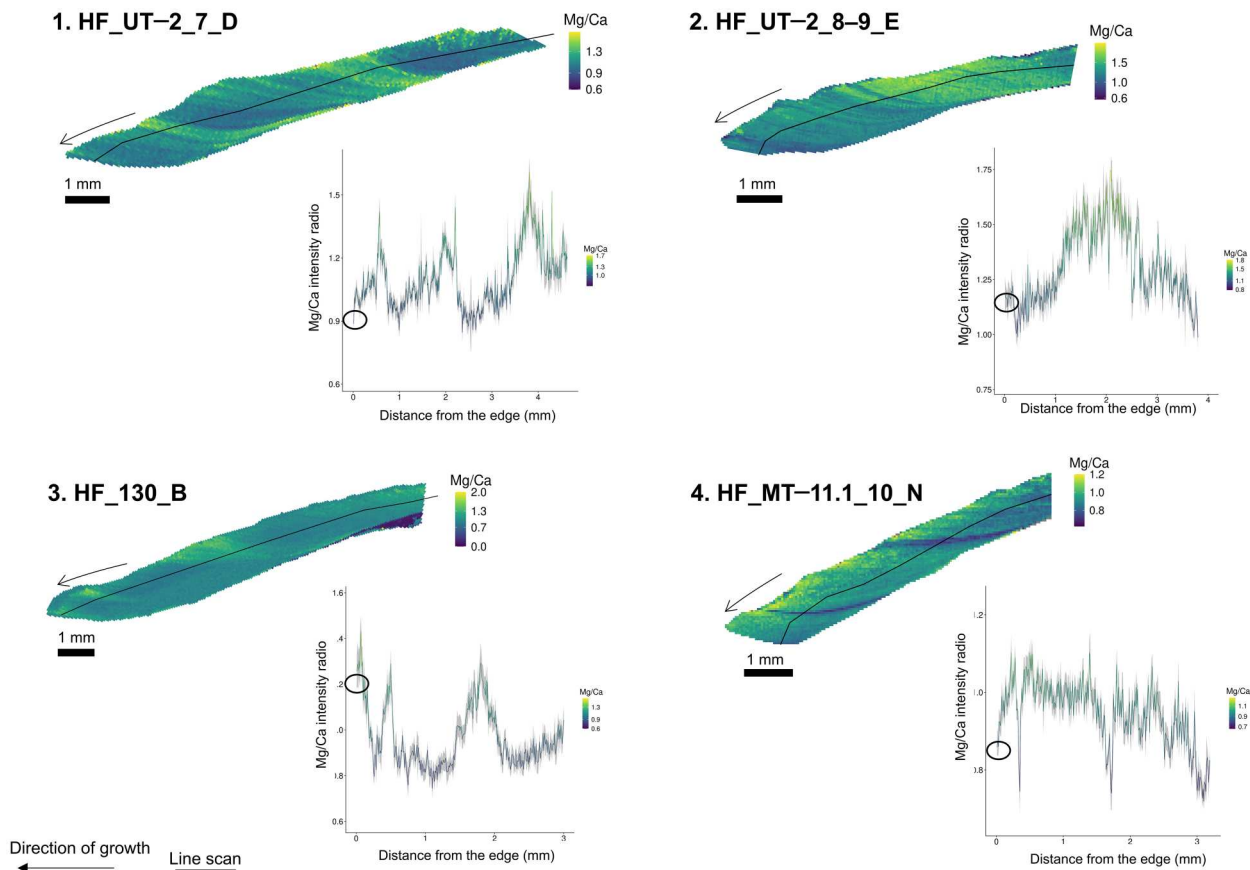
### Seasonal Patterns of Resource Exploitation at the Haua Fteah

Previous studies based on the analysis of *P. turbinatus* concluded that marine molluscs represented a dietary supplement during the winter months of the year in the Capsian period, when terrestrial resources were less available (Prendergast et al. 2016a). However, in this study, limpet remains indicate a broader seasonal collection pattern. According to our results, *P. caerulea* was collected mainly during winter and autumn, but also shows collection during spring and summer. This evidence suggests that, although mollusc exploitation was concentrated in winter, human groups also collected limpets the rest of the year, reflecting a more balanced use of intertidal resources. Thus, the exploitation of *P. caerulea* may have coincided with terrestrial hunting and plant gathering during the warmer months, reflecting a complementary and more stable presence of marine molluscs in the diet rather than a restricted seasonal pattern.

During the Neolithic of phase UT-2 (8–7.5 ka cal. BP), the collection of *P. turbinatus* was mainly represented during winter (Prendergast et al. 2016a). In the case of *P. caerulea*, winter is also the most frequent season, but the rest of the seasons are also represented. After winter collection, there is a significant contribution of autumn, and to a lesser extent, summer and spring collection. This seasonal pattern of limpets indicates that, although marine molluscs were mainly collected during the winter months, human groups maintained their access to intertidal areas and were collecting molluscs at other moments of the year, similar to during the Capsian.

This continuity in the seasonal distribution of limpets, accompanied by increased resource use as indicated by the reduction in average shell size (Hunt et al. 2011), suggests that marine molluscs appear to be a consistent resource throughout the year, with mollusc collection showing different patterns depending on the taxa, and resources increasingly integrated into Neolithic subsistence strategies.

The continued emphasis on mollusc exploitation in the Neolithic also occurred in the context of a continued reliance on wild terrestrial and botanical resources



**Figure 5.** Mg/Ca maps and line-scans along the growth direction of the posterior and anterior sections of four specimens of *P. caerulea* (season of collection: specimen 1, collected in winter; 2: spring; 3: summer; and 4: autumn). The maps follow a colour scale ranging from purple for the lowest ratios to yellow for the highest ratios. The grey shading shows the error bars derived from the standard deviation. The black circle indicates the season of collection.

(Lucarini et al. 2016), as well as the appearance of domesticated caprines with no evidence of cultivated plants (Barker et al. 2012).

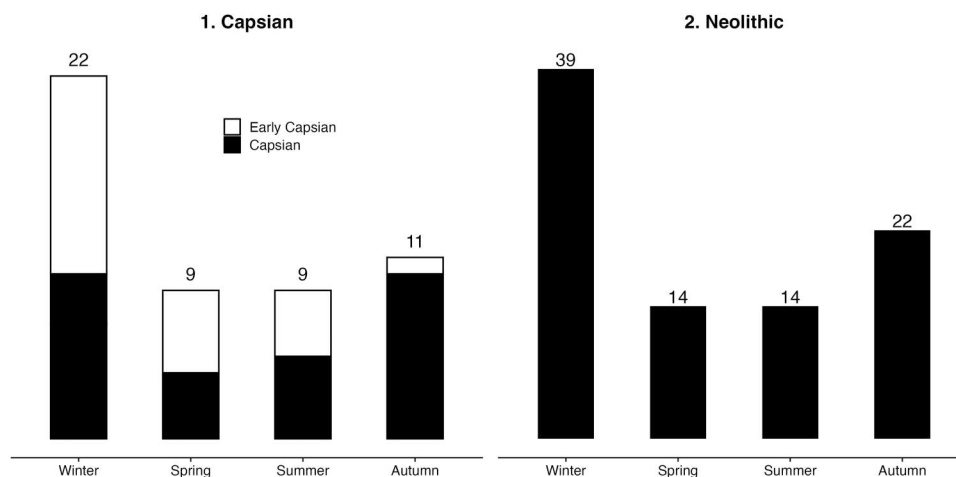
### Interpretations of the Differences in Mollusc Species Collection

Comparisons with other Mediterranean and Atlantic Mesolithic and Neolithic sites provide valuable

insights into species-specific seasonal collection patterns. For *P. caerulea*, comparable examples of the same genus have been recorded on the Atlantic façade of Mesolithic sites in northern Iberia, such as *Patella depressa* Pennant, 1777, which exhibits a focused cold-season exploitation pattern (García-Escárczaga et al. 2024). The seasonality pattern of *P. turbinatus* from the Haua Fteah has also been documented in other parts of the Mediterranean. During the

**Table 2.** Seasonal distribution of *P. caerulea* collection from the Capsian to the Neolithic periods, indicating the number of samples and percentages to each season.

CPP phase	McBurney Spit/CPP Context	Culture	Modelled age (ka cal. BP)	Winter	Spring	Summer	Autumn
MT-10	XI	Early Capsian	12–11.2	7	5	2	1
	78			5	–	2	–
MT-11	X	Capsian	Post 11.2	7	4	5	10
UT-1 135		Capsian	11.5–8.5	3	–	–	–
<b>Total Capsian</b>				<b>22</b>	<b>9</b>	<b>9</b>	<b>11</b>
			%	<b>43</b>	<b>18</b>	<b>18</b>	<b>22</b>
UT-2 VII		Neolithic	8–5.5	17	2	1	9
VI–VIII				–	1	3	1
VIII–IX				2	4	3	3
IX				8	6	3	5
130				2	–	1	3
131				4	–	2	1
132				4	–	1	–
133				2	1	–	–
<b>Total Neolithic</b>				<b>39</b>	<b>14</b>	<b>14</b>	<b>22</b>
			%	<b>44</b>	<b>16</b>	<b>16</b>	<b>25</b>



**Figure 6.** Seasonality patterns by Mg/Ca ratios represented as the number of specimens organised by Early Capsian (white colour) and Capsian (black colour) and Neolithic (black colour) phases at the Haua Fteah.

Mesolithic and Neolithic periods, in Grotta della Seratura, Grotta di Cala Mancina, Grotta d'Oriente, Grotta dell'Uzzo, and Grotta delle Uccerie in south-western Italy and Sicily, collection took place mostly during winter and autumn (Colonese et al. 2009; 2018; Mannino et al. 2007). In the case of Vela Spila in Croatia, shellfish collecting occurred mainly in summer and autumn during the Mesolithic, and in autumn and winter during the Neolithic (Branscombe, Bosch, and Miracle 2021).

On the Atlantic Iberian Peninsula, Mesolithic sites have preserved topshells of the same genus, such as *Phorcus lineatus* (da Costa, 1778), which show a restricted collection pattern focused on winter and autumn (García-Escárczaga et al. 2019, 2025). Other records, in the case of *Mytilus galloprovincialis* (Lamarck, 1819), indicate more variable seasonal collection patterns, although with a preference for the colder months (Milano et al. 2022).

The different collection patterns of *P. caerulea* and *P. turbinatus* at the Haua Fteah can be interpreted in six ways:

- (1) *P. turbinatus* was a fallback resource, suggesting that they would only be collected when the primary dietary base, large mammals, was less available (Prendergast et al. 2016a). Compared with *P. caerulea*, which can be scooped out of its shell, *P. turbinatus* also requires cooking first, before the meat can be removed.
- (2) Social practices may also have significantly influenced the marked seasonality of *P. turbinatus* collection. Some researchers propose that activities such as feasting and rituals could impact consumption patterns of specific animals (Milner 2005). However, data from the Haua Fteah (Prendergast et al. 2016a) do not support this interpretation, as the seasonal collecting of *P. turbinatus* took place mainly during winter throughout the entire Capsian and Neolithic sequence. Therefore, it is difficult to interpret its consumption as being exclusive to particular events.
- (3) The seasonal change in taste perception could have also influenced this pattern, according to Mannino et al. (2014). However, taste perception is subjective, and it is very challenging to apply its effects to the entire span of the Capsian and Neolithic.
- (4) The division of labour has been considered to explain the absence or low presence of *P. turbinatus* specimens collected during autumn, spring and summer seasons, as those responsible for these gathering activities during summer months might have been engaged in other tasks (Mannino et al. 2011). This does not apply to the Haua Fteah, where *P. caerulea* was collected during spring and summer from the same part of the intertidal zone. It is possible that different individuals were responsible for collecting different species. For example, *Phorcus* spp., which are easier to detach from the rocks than limpets, may have been gathered by children or other individuals, while *Patella* spp. collection involved different collectors. However, this organisation of labour cannot be tested with the available archaeological evidence.
- (5) *Patella* spp. provide higher meat yields than *Phorcus* spp. according to modern studies (Dupont and Gruet 2002; Dupont and Gruet 2022; García-Escárczaga and Gutiérrez-Zugasti 2021). Moreover, looking at meat yield variations, modern studies indicate that *P. turbinatus* exhibits a long reproductive season in the Mediterranean, lasting from April to June and from October to December (Kücükdermenci et al. 2025). This indicates that winter collection coincides with the period of gametogenesis,



**Figure 7.** Modern specimens of *Phorcus* spp. and *Patella* spp. in the intertidal zone. Photograph taken by Rosa Arniz-Mateos.

when individuals have both higher absolute flesh weight and higher lipid content, potentially maximising the nutritional return from collection. For *P. caerulea*, modern studies on the coast of Tunisia have identified a male spawning from March to August and April to June, and female spawning from April to July, with a secondary spawning in January (Belkhodja et al. 2011). However, the period of spawning may vary locally due to environmental and biological factors and may change over time. Currently, there is no information about the gametogenesis period that may coincide with the periods of higher meat yield on the coast of Libya that could explain the predominant winter collection in the Haua Fteah. It is possible that, in a context of environmental change, limpets would be more likely to be collected throughout the year compared to topshells due to their greater energetic return and variability in their meat yield.

- (6) Archaeological visibility may be another factor to consider, given that both species coexisted in the same intertidal zone (Figure 7). Their processing

techniques, however, differed. Topshells typically require heating or boiling to facilitate the extraction of the soft tissues from their spiral shells, a practice that appears to be reflected in the high proportion of thermally altered topshells in the McBurney collection. Limpets, by contrast, can be consumed raw, and their soft tissues are immediately accessible once detached from the rock. It is possible that a quantity of limpets was consumed near the collecting locations, on the beach, while topshells were likely transported to the Haua Fteah for meat extraction, which would bias the number of preserved shells towards topshells. This bias could be seasonal, if, for instance, the location of topshell processing moved into the cave during winter. However, this hypothesis is difficult to test, as it relies on the limited evidence available in the shell assemblages from the archaeological sites.

## Conclusion

This study analysed seasonal collection patterns of *P. caerulea* shells from the Capsian and Neolithic phases

at the Haua Fteah cave. The results highlight the value of this approach for understanding human subsistence strategies and the role of shellfish exploitation in past lifeways. Our findings reveal that, despite the similarity in the patterns of shell collection seasonality observed for the different taxa, our data suggest the existence of some variability in the collection strategies. The strongly marked winter-autumn harvesting of *P. turbinatus* contrasts with the broader, less restricted, seasonal pattern of *P. caerulea*, which is consistently represented in at least two seasons at the Haua Fteah (except in the Capsian CPP context 135), in line with other examples of shellfish exploitation in the Mediterranean and Atlantic during the Mesolithic and Neolithic periods. The evidence suggests that, although marine molluscs were preferentially exploited during winter and autumn, limpet collection represents a more stable and reliable resource exploited year-round. Their collection likely complemented the general subsistence, forming part of a diversified diet. These differences in seasonal species selection underscore the complexity of subsistence strategies, revealing collection strategies that were likely shaped by the availability of other food resources, different mollusc processing techniques, specific periods when certain foods were preferentially collected, potentially because of higher meat yields and potentially socio-economic factors such as labour division and dietary tastes. The similar shellfish-gathering behaviours evidenced in this study for the Capsian and Neolithic phases of occupation in the Haua Fteah accord with the other subsistence data from the site indicating fundamental continuity in patterns of hunting, fishing and gathering from the Capsian (Latest Pleistocene and Early Holocene) to the Middle Holocene Neolithic, apparently unaffected by the introduction of domestic sheep and goats in the latter.

## Disclosure Statement

No potential conflict of interest was reported by the authors.

## Acknowledgements

We would like to express our gratitude to the Museum of Archaeology and Anthropology, University of Cambridge for the permit granted for the analysis of the shell specimens from McBurney's excavations. We would like to thank the Applied Photonics Laboratory of the Institute of Electronic Structure and Laser, Foundation for Research and Technology–Hellas (FORTH), for their assistance and technical support with the LIBS system. We also thank Guillermo Alzate-Casallas (ICArEHB, University of Algarve) for his help during the graphic design process. We are grateful to the reviewers for their comments, which have improved the manuscript.

## Funding

RAM and NH were supported by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) under the Emmy Noether Program (project number: 439799406). The CPP fieldwork was funded primarily by the Society for Libyan Studies (now the British Institute for Libyan and North African Studies) and the European Research Council Advanced Investigator grant 230421 TRANS-NAP project 'Cultural Transformations and Environmental Transitions in North African Prehistory' awarded to GB.

## Credit Authorship

**Rosa Arniz-Mateos:** Writing – original draft, methodology, investigation, formal analysis and conceptualization. **Chris Hunt:** Writing – review, validation. **Graeme Barker:** Writing – original draft, review and editing and validation. **Niklas Hausmann:** Writing – original draft, methodology, investigation, validation, supervision, resources, funding acquisition, conceptualization.

## Notes on Contributors

**Rosa Arniz-Mateos** is a postdoctoral researcher in the DFG–Emmy Noether project SEAFRONT at LEIZA, specialising in archaeomalacology and the study of marine resource exploitation by prehistoric human groups. Her research focuses on how past climatic conditions shaped human lifeways, with particular attention to Mesolithic and Neolithic Europe. Her work has been conducted across Mediterranean and Atlantic regions.

**Chris O. Hunt** is an Emeritus Professor at Liverpool John Moores University, with broad research experience spanning Quaternary science, archaeological science, palynology, sedimentology, molluscs, palaeoecology, and palaeoenvironments. His research has been conducted across Europe, the Middle East, North Africa, Southeast Asia, and North America.

**Graeme Barker** is a Disney Professor of Archaeology Emeritus at the McDonald Institute for Archaeological Research, specialising in the relationships between past human societies and their environments from Palaeolithic hunter-gatherers to historical and present-day societies. His work has been conducted in Borneo, Italy, Jordan, Libya, and Iraqi Kurdistan, where he has led large interdisciplinary fieldwork teams.

**Niklas Hausmann** is the research leader of the DFG–Emmy Noether project SEAFRONT at LEIZA, specialising in the analysis of high-resolution climate archives preserved in mollusc shells. His research focuses on the geochemical analysis of marine shells to reconstruct short-term climatic fluctuations in the past. His work has been conducted across Europe, North Africa, the Middle East, the Asian Pacific, and the Americas.

## ORCID

**Rosa Arniz-Mateos**  <http://orcid.org/0000-0002-1387-8651>

**Chris O. Hunt**  <http://orcid.org/0000-0003-0330-8871>

**Graeme Barker**  <http://orcid.org/0000-0002-2678-4283>

**Niklas Hausmann**  <http://orcid.org/0000-0002-4381-8334>

## References

- Andrus, C. 2011. "Shell Midden Sclerochronology." *Quaternary Science Reviews* 30:2892–2905. <https://doi.org/10.1016/j.quascirev.2011.07.016>.
- Bailey, G., and N. Milner. 2002. "Coastal Hunter-Gatherers and Social Evolution" *Before Farming* 2002 (3–4): 1–22. <https://doi.org/10.3828/bfarm.2002.3-4.1>.
- Bailey, G. N., and N. C. Flemming. 2008. "Archaeology of the Continental Shelf: Marine Resources, Submerged Landscapes and Underwater Archaeology." *Quaternary Science Reviews* 27 (23–24): 2153–2165. <https://doi.org/10.1016/j.quascirev.2008.08.012>.
- Barker, G., A. Antoniadou, S. J. Armitage, I. Brooks, I. Candy, K. Connell, K. Douka, et al. 2010. "The Cyrenaican Prehistory Project 2010: The Fourth Season of Investigations of the Haua Fteah Cave and Its Landscape, and Further Results from the 2007–2009 Fieldwork." *Libyan Studies* 41:63–88. <https://doi.org/10.1017/S0263718900000273>.
- Barker, G., A. Antoniadou, H. Barton, I. Brooks, I. Candy, N. Drake, L. Farr, et al. 2009. "The Cyrenaican Prehistory Project 2009: The Third Season of Investigations of the Haua Fteah Cave and Its Landscape, and Further Results from the 2007–2008 Fieldwork." *Libyan Studies* 40:55–94. <https://doi.org/10.1017/S0263718900004519>.
- Barker, G., L. Basell, I. Brooks, L. Burn, C. Cartwright, F. Cole, J. Davison, et al. 2008. "The Cyrenaican Prehistory Project 2008: The Second Season of Investigations of the Haua Fteah Cave and Its Landscape, and Further Results from the Initial (2007) Fieldwork." *Libyan Studies* 39:175–221. <https://doi.org/10.1017/S0263718900010074>.
- Barker, G., P. Bennett, L. Farr, E. Hill, C. O. Hunt, G. Lucarini, J. Morales, et al. 2012. "The Cyrenaican Prehistory Project 2012: The Fifth Season of Investigations of the Haua Fteah Cave." *Libyan Studies* 43:115–136. <https://doi.org/10.1017/S026371890000008X>.
- Barker, G., and C. Hunt. 2025. "Living with Climate Change in North African Prehistory: The Green Mountain of Cyrenaica as Refugium or cul-de-sac? Chapter 3." In *Echoes of Africa's Past. Archaeological Explorations in the Anthropocene*, edited by S. di Lernia, 81–99. Vol. 10 of *Arid Zone Archaeology Monographs*. Florence: Insegna del Giglio. <https://doi.org/10.36153/aza10.03>.
- Belkhdja, H., M. H. Jaafoura, H. Missaoui, and M. S. Romdhane. 2011. "Histological Investigation of the Reproductive Cycle of the Limpet *Patella caerulea* Linnaeus, 1758." *Cahiers de Biologie Marine* 52 (3): 279–290.
- Bosch, M. D., M. A. Mannino, A. L. Prendergast, T. C. O'Connell, B. Demarchi, S. M. Taylor, L. Niven, J. van der Plicht, and J. J. Hublin. 2015. "New Chronology for Ksar 'Akil (Lebanon) Supports Levantine Route of Modern Human Dispersal into Europe." *Proceedings of the National Academy of Sciences* 112 (25): 7683–7688. <https://doi.org/10.1073/pnas.1501529112>.
- Branscombe, T., M. Bosch, and P. Miracle. 2021. "Seasonal Shellfishing across the East Adriatic Mesolithic-Neolithic Transition: Oxygen Isotope Analysis of *Phorcus turbinatus* from Vela Spila (Croatia)." *Environmental Archaeology* 26 (3): 497–510. <https://doi.org/10.1080/14614103.2020.1721695>.
- Broadhurst, C. L., Y. Wang, M. A. Crawford, S. C. Cunnane, J. E. Parkington, and W. F. Schmidt. 2002. "Brain-specific Lipids from Marine, Lacustrine, or Terrestrial Food Resources: Potential Impact on Early African Homo Sapiens." *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology* 131 (4): 653–673. [https://doi.org/10.1016/S1096-4959\(02\)00002-7](https://doi.org/10.1016/S1096-4959(02)00002-7).
- Carlson, B. A., and J. D. Kingston. 2007. "Docosahexaenoic Acid, the Aquatic Diet, and Hominin Encephalization: Difficulties in Establishing Evolutionary Links." *American Journal of Human Biology* 19 (1): 132–141. <https://doi.org/10.1002/ajhb.20579>.
- Ciuti, S., A. Pipia, S. Grignolio, F. Ghiandai, and M. Apollonio. 2009. "Space use, Habitat Selection and Activity Patterns of Female Sardinian Mouflon (*Ovis orientalis musimon*) during the Lambing Season." *European Journal of Wildlife Research* 55 (6): 589–595. <https://doi.org/10.1007/s10344-009-0279-y>.
- Cobo, A., A. García-Escárcaga, I. Gutiérrez-Zugasti, J. Setién, M. R. González-Morales, and J. M. López-Higuera. 2017. "Automated Measurement of Magnesium/Calcium Ratios in Gastropod Shells Using Laser-Induced Breakdown Spectroscopy for Paleoclimatic Applications." *Applied Spectroscopy* 71 (4): 591–599. <https://doi.org/10.1177/0003702816687570>.
- Colonese, A. C., M. A. Mannino, D. E. Mayer, B.-Y. Fa, D. A. Finlayson, J. C. Lubell, D. Stiner, and M. C. 2011. "Marine Mollusc Exploitation in Mediterranean Prehistory: An Overview." *Quaternary International* 239 (1–2): 86–103. <https://doi.org/10.1016/j.quaint.2010.09.001>.
- Colonese, A. C., S. Troelstra, P. Ziveri, F. Martini, D. Lo Vetro, and S. Tommasini. 2009. "Mesolithic Shellfish Exploitation in SW Italy: Seasonal Evidence from the Oxygen Isotopic Composition of *Osilinus turbinatus* Shells." *Journal of Archaeological Science* 36 (9): 1935–1944. <https://doi.org/10.1016/j.jas.2009.04.021>.
- Colonese, A. C., D. L. Vetro, W. Landini, Z. Di Giuseppe, N. Hausmann, B. Demarchi, C. d'Angelo, et al. 2018. "Late Pleistocene-Holocene Coastal Adaptation in Central Mediterranean: Snapshots from Grotta d'Oriente (NW Sicily)." *Quaternary International* 493:114–126. <https://doi.org/10.1016/j.quaint.2018.06.018>.
- Deith, M. R., and J. C. Shackleton. 1988. "The Contribution of Shells to Site Interpretations: Approaches to Shell Material from Franchthi Cave." In *Conceptual Issues in Environmental Archaeology*, edited by J. L. Bintliff, D. A. Davidson and E. G. Grant, 49–58. Edinburgh: University Press.
- Douka, K., R. Grün, Z. Jacobs, C. Lane, L. Farr, C. O. Hunt, R. Inglis, et al. 2014. "The Chronostratigraphy of the Haua Fteah Cave (Cyrenaica, Northeast Libya)." *Journal of Human Evolution* 66:39–63. <https://doi.org/10.1016/j.jhevol.2013.10.001>.
- Dupont, C., and Y. Gruet. 2002. "Estimation de la ressource alimentaire en masse de chair d'après les restes de coquilles: applications aux berniques *Patella* sp. et au "bigorneau" *Monodonta lineata* de sites mésolithiques et néolithiques." *Revue D'archéométrie* 26 (1): 93–112. <https://doi.org/10.3406/arsci.2002.1026>.
- Dupont, C., and Y. Gruet. 2022. "Why Mesolithic Populations Started Eating Crabs on the European Atlantic Façade Only over the Past 15 Years?" *Open Archaeology* 8 (1): 670–695. <https://doi.org/10.1515/opar-2022-0255>.
- Emiliani, C., and T. Mayeda. 1964. "Oxygen Isotopic Analysis of Some Molluscan Shells from Fossil Littoral Deposits of Pleistocene Age." *American Journal of Science* 262 (1): 107–113. <https://doi.org/10.2475/ajs.262.1.107>.

- Erlandson, J. M. 1988. "The Role of Shellfish in Prehistoric Economies: A Protein Perspective." *American Antiquity* 53 (1): 102–109. <https://doi.org/10.2307/281156>.
- Fenger, T., D. Surge, B. Schöne, and N. Milner. 2007. "Sclerochronology and Geochemical Variation in Limpet Shells (*Patella vulgata*): A New Archive to Reconstruct Coastal Sea Surface Temperature." *Geochemistry, Geophysics, Geosystems* 8 (7): 1–17. <https://doi.org/10.1029/2006GC001488>.
- Ferguson, J. E., G. M. Henderson, D. A. Fa, J. C. Finlayson, and N. R. Charnley. 2011. "Increased Seasonality in the Western Mediterranean during the Last Glacial from Limpet Shell Geochemistry." *Earth and Planetary Science Letters* 308 (3–4): 325–333. <https://doi.org/10.1016/j.epsl.2011.05.054>.
- Freitas, P., L. J. Clarke, H. Kennedy, C. Richardson, and F. Abrantes. 2005. "Mg/Ca, Sr/Ca, and Stable-Isotope ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) Ratio Profiles from the fan Mussel *Pinna nobilis*: Seasonal Records and Temperature Relationships." *Geochemistry, Geophysics, Geosystems* 6 (4): 1–16. <https://doi.org/10.1029/2004GC000872>.
- García-Escárzaga, A., L. J. Clarke, I. Gutiérrez-Zugasti, M. R. González-Morales, M. Martínez, J.-M. López-Higuera, and A. Cobo. 2018. "Mg/Ca Profiles within Archaeological Mollusc (*Patella vulgata*) Shells: Laser-Induced Breakdown Spectroscopy Compared to Inductively Coupled Plasma-Optical Emission Spectrometry." *Spectrochimica Acta Part B: Atomic Spectroscopy* 148:8–15. <https://doi.org/10.1016/j.sab.2018.05.026>.
- García-Escárzaga, A., and I. Gutiérrez-Zugasti. 2021. "The Role of Shellfish in Human Subsistence during the Mesolithic of Atlantic Europe: An Approach from Meat Yield Estimations." *Quaternary International* 584:9–19. <https://doi.org/10.1016/j.quaint.2020.03.003>.
- García-Escárzaga, A., I. Gutiérrez-Zugasti, R. Arniz-Mateos, D. Cuenca-Solana, M. R. González-Morales, J. Ilgner, M. Lucas, A. C. Colonese, and P. Roberts. 2024. "Seasonal Exploitation of Intertidal Resources at El Mazo (N Iberia) Reveals Optimized Human Subsistence Strategies during the Mesolithic in Atlantic Europe." *Archaeological and Anthropological Sciences* 16:76. <https://doi.org/10.1007/s12520-024-01960-3>.
- García-Escárzaga, A., I. Gutiérrez-Zugasti, A. Cobo, D. Cuenca-Solana, J. Martín-Chivelet, P. Roberts, and M. R. González-Morales. 2019. "Stable Oxygen Isotope Analysis of *Phorcus lineatus* (da Costa, 1778) as a Proxy for Foraging Seasonality during the Mesolithic in Northern Iberia." *Archaeological and Anthropological Sciences* 11 (10): 5631–5644. <https://doi.org/10.1007/s12520-019-00880-x>.
- García-Escárzaga, A., A. León-Cristóbal, E. Álvarez-Fernández, A. C. Colonese, A. Arrizabalaga, M. J. Iriarte-Chiapusso, E. Iriarte, and M. A. Fano. 2025. "Strengthening the Evidence for Seasonal Intertidal Exploitation in Mesolithic Europe and New Insights into Early Holocene Environmental Conditions in the Bay of Biscay from the Oxygen Isotope Composition of *Phorcus lineatus* (da Costa, 1778) Shells." *Palaeogeography, Palaeoclimatology, Palaeoecology* 659:112624. <https://doi.org/10.1016/j.palaeo.2024.112624>.
- García-Escárzaga, A., S. Moncayo, I. Gutiérrez-Zugasti, M. R. González-Morales, J. Martín-Chivelet, and J. O. Cáceres. 2015. "Mg/Ca Ratios Measured by Laser Induced Breakdown Spectroscopy (LIBS): A New Approach to Decipher Environmental Conditions." *Journal of Analytical Atomic Spectrometry* 30 (9): 1913–1919. <https://doi.org/10.1039/C5JA00168D>.
- Graniero, L. E., D. Surge, D. P. Gillikin, I. B. i Godino, and M. Álvarez. 2017. "Assessing Elemental Ratios as a Paleotemperature Proxy in the Calcite Shells of Patelloid Limpets." *Palaeogeography, Palaeoclimatology, Palaeoecology* 465:376–385. <https://doi.org/10.1016/j.palaeo.2016.10.021>.
- Gutiérrez-Zugasti, I., S. H. Andersen, A. C. Araújo, C. Dupont, N. Milner, and A. M. Monge-Soares. 2011. "Shell Midden Research in Atlantic Europe: State of the art, Research Problems and Perspectives for the Future." *Quaternary International* 239 (1): 70–85. <https://doi.org/10.1016/j.quaint.2011.02.031>.
- Hampy, D. B. 1978. "Home Range and Seasonal Movement of Barbary Sheep in the Palo Duro Canyon." Doctoral dissertation, Texas Tech University.
- Hausmann, N., A. L. Prendergast, A. Lemonis, J. Zech, P. Roberts, P. Siozos, and D. Anglos. 2019. "Extensive Elemental Mapping Unlocks Mg/Ca Ratios as Climate Proxy in Seasonal Records of Mediterranean Limpets." *Scientific Reports* 9 (1): 3698. <https://doi.org/10.1038/s41598-019-39959-9>.
- Hausmann, N., P. Siozos, A. Lemonis, A. C. Colonese, H. K. Robson, and D. Anglos. 2017. "Elemental Mapping of Mg/Ca Intensity Ratios in Marine Mollusc Shells Using Laser-Induced Breakdown Spectroscopy." *Journal of Analytical Atomic Spectrometry* 32 (8): 1467–1472. <https://doi.org/10.1039/C7JA00131B>.
- Hausmann, N., D. Surge, and I. B. i Godino. 2024. "Confirmation of Mg/Ca Ratios as Palaeothermometers in Atlantic Limpet Shells." *Palaeogeography, Palaeoclimatology, Palaeoecology* 655:112538. <https://doi.org/10.1016/j.palaeo.2024.112538>.
- Hausmann, N., D. Theodoraki, V. Piñon, P. Siozos, A. Lemonis, and D. Anglos. 2023. "Applying Laser Induced Breakdown Spectroscopy (LIBS) and Elemental Imaging on Marine Shells for Archaeological and Environmental Research." *Scientific Reports* 13 (1): 19812. <https://doi.org/10.1038/s41598-023-46453-w>.
- Hunt, C., J. Davison, R. Inglis, L. Farr, T. Reynolds, D. Simpson, H. el-Rishi, and G. Barker. 2010. "Site Formation Processes in Caves: The Holocene Sediments of the Haua Fteah, Cyrenaica, Libya." *Journal of Archaeological Science* 37 (7): 1600–1611. <https://doi.org/10.1016/j.jas.2010.01.021>.
- Hunt, C. O., T. G. Reynolds, H. A. El-Rishi, A. Buzaian, E. Hill, and G. W. Barker. 2011. "Resource Pressure and Environmental Change on the North African Littoral: Epipalaeolithic to Roman Gastropods from Cyrenaica, Libya." *Quaternary International* 244 (1): 15–26. <https://doi.org/10.1016/j.quaint.2011.04.045>.
- Inglis, R. H. 2011. "Human Occupation and Changing Environments during the Middle to Later Stone Ages: Soil Micromorphology at the Haua Fteah, Libya." Doctoral dissertation.
- Jacobs, Z., L. Li, L. Farr, E. Hill, C. Hunt, S. Jones, R. Rabett, et al. 2017. "The Chronostratigraphy of the Haua Fteah Cave (Cyrenaica, Northeast Libya) — Optical Dating of Early Human Occupation during Marine Isotope Stages 4, 5 and 6." *Journal of Human Evolution* 105:69–88. <https://doi.org/10.1016/j.jhevol.2017.01.008>.
- Klein, R., and K. Scott. 1986. "Re-analysis of Faunal Assemblages from the Haua Fteah and Other Late Quaternary Archaeological Sites in Cyrenaican Libya." *Journal of Archaeological Science* 13:515–542. [https://doi.org/10.1016/0305-4403\(86\)90038-5](https://doi.org/10.1016/0305-4403(86)90038-5).
- Kücükdermenci, A., A. Lök, S. Serdar, S. Acarlı, A. Kirtik, and S. Hamzaçebi. 2025. "Reproductive Pattern of the

- Phorcus turbinatus* (Born, 1778) on Littoral Zones in Aegean Sea.” *Aquaculture International* 33 (2): 93. <https://doi.org/10.1007/s10499-024-01718-7>.
- Lucarini, G., A. Radini, H. Barton, and G. Barker. 2016. “The Exploitation of Wild Plants in Neolithic North Africa. Use-Wear and Residue Analysis on Non-knapped Stone Tools from the Haua Fteah Cave, Cyrenaica, Libya.” *Quaternary International* 410:77–92. <https://doi.org/10.1016/j.quaint.2015.11.109>.
- MacDonald, K. C. 1987. “The Avifauna of the Haua Fteah (Libya).” *Archaeozoologia* 9:83–e102.
- Mannino, M., K. Thomas, M. Leng, M. Piperno, S. Tusa, and A. Tagliacozzo. 2007. “Marine Resources in the Mesolithic and Neolithic at the Grotta Dell’uzzo (Sicily): Evidence from Isotope Analyses of Marine Shells\*.” *Archaeometry* 49:117–133. <https://doi.org/10.1111/j.1475-4754.2007.00291.x>.
- Mannino, M. A., K. D. Thomas, E. R. Crema, and M. J. Leng. 2014. “A Matter of Taste? Mode and Periodicity of Marine Mollusc Exploitation on the Mediterranean Island of Favignana (Ègadi Islands, Italy) during Its Isolation in the Early Holocene.” *Archaeofauna* 23 (1): 133–147. <https://doi.org/10.15366/archaeofauna2014.23.009>.
- Mannino, M. A., K. D. Thomas, M. J. Leng, R. Di Salvo, and M. P. Richards. 2011. “Stuck to the Shore? Investigating Prehistoric Hunter-Gatherer Subsistence, Mobility and Territoriality in a Mediterranean Coastal Landscape through Isotope Analyses on Marine Mollusc Shell Carbonates and Human Bone Collagen.” *Quaternary International* 244 (1): 88–104. <https://doi.org/10.1016/j.quaint.2011.05.044>.
- McBurney, C. B. M. 1967. *The Haua Fteah (Cyrenaica) and the Stone Age of the South - East Mediterranean*. Cambridge: Cambridge University Press.
- Milano, S., B. R. Schöne, M. R. González-Morales, and I. Gutiérrez-Zugasti. 2022. “Temporal and Spatial Variability of Prehistoric Aquatic Resource Procurement: A Case Study from Mesolithic Northern Iberia.” *Scientific Reports* 12 (1): 3111. <https://doi.org/10.1038/s41598-022-07239-8>.
- Milner, N. 2005. “Seasonal Consumption Practices in the Mesolithic: Economic, Environmental, Social or Ritual?” In *Mesolithic Studies at the Beginning of the 21st Century*, edited by N. Milner and P. C. Woodman, 56–67. Oxford: Oxbow Books.
- Milner, N. 2009. “Mesolithic Consumption Practices: Food for Thought.” *Journal of Nordic Archaeological Science* 16:49–64.
- Mirapeix, J., R. Arniz-Mateos, A. García-Escárgaza, I. Gutierrez-Zugasti, J. M. López-Higuera, and A. Cobo. 2025a. “Virtual Sampling: Archaeological Implications of a New Technique for Elemental Mapping of Mg/Ca Ratios in Marine Mollusc Shells.” *Journal of Archaeological Science* 173:106123. <https://doi.org/10.1016/j.jas.2024.106123>.
- Mirapeix, J., R. Arniz-Mateos, D. Theodoraki, A. García-Escárgaza, V. Piñon, I. Gutiérrez-Zugasti, N. Hausmann, and A. Cobo. 2025b. “A Comparative Analysis of Elemental Imaging of Marine Mollusc Shells Using Laser Induced Breakdown Spectroscopy.” *Microchemical Journal* 213:113756. <https://doi.org/10.1016/j.microc.2025.113756>.
- Prendergast, A., R. Stevens, T. O’Connell, C. Hunt, B. Schöne, and G. Barker. 2016a. “Changing Patterns of Eastern Mediterranean Shellfish Exploitation in the Late Glacial and Early Holocene: Oxygen Isotope Evidence from Gastropod in Epipaleolithic to Neolithic Human Occupation Layers at the Haua Fteah Cave, Libya.” *Quaternary International* 407:80–93. <https://doi.org/10.1016/j.quaint.2015.09.035>.
- Prendergast, A. L., and B. R. Schöne. 2017. “Oxygen Isotopes from Limpet Shells: Implications for Palaeothermometry and Seasonal Shellfish Foraging Studies in the Mediterranean.” *Palaeogeography, Palaeoclimatology, Palaeoecology* 484:33–47. <https://doi.org/10.1016/j.palaeo.2017.03.007>.
- Prendergast, A. L., R. E. Stevens, T. C. O’Connell, E. A. Hill, C. O. Hunt, and G. W. Barker. 2016b. “A Late Pleistocene Refugium in Mediterranean North Africa? Palaeoenvironmental Reconstruction from Stable Isotope Analyses of Land Snail Shells (Haua Fteah, Libya).” *Quaternary Science Reviews* 139:94–109. <https://doi.org/10.1016/j.quascirev.2016.02.014>.
- Reade, H., R. E. Stevens, T. C. O’Connell, and G. Barker. 2016. “Pleistocene and Holocene Herbivore Diets and Palaeoenvironments in the Gebel Akhdar (Libya): Implications for Past Human Populations.” *Palaeogeography, Palaeoclimatology, Palaeoecology* 449:62–78. <https://doi.org/10.1016/j.palaeo.2016.02.003>.
- Schweikhardt, P., B. L. Ingram, K. Lightfoot, and E. Luby. 2011. “Geochemical Methods for Inferring Seasonal Occupation of an Estuarine Shellmound: A Case Study from San Francisco Bay.” *Journal of Archaeological Science* 38 (9): 2301–2312. <https://doi.org/10.1016/j.jas.2011.04.004>.
- Stringer, C. B., J. C. Finlayson, R. N. E. Barton, Y. Fernández-Jalvo, I. Cáceres, R. C. Sabin, E. J. Rhodes, et al. 2008. “Neanderthal Exploitation of Marine Mammals in Gibraltar.” *Proceedings of the National Academy of Sciences* 105 (38): 14319–14324. <https://doi.org/10.1073/pnas.0805474105>.
- Theodoraki, D., M. A. Mannino, A. L. Prendergast, B. R. Schöne, and N. Hausmann. 2026. “Multi-regional Calibration of *Patella caerulea* as a Palaeothermometer Using Oxygen Isotope Values and Mg/Ca Ratios.” *The Holocene* 36 (1): 37–50. <https://doi.org/10.1177/09596836251378034>.
- Thomas, K. D. 2015. “Molluscs Emergent, Part I: Themes and Trends in the Scientific Investigation of Mollusc Shells as Resources for Archaeological Research.” *Journal of Archaeological Science* 56:133–140. <https://doi.org/10.1016/j.jas.2015.01.024>.
- Verdún-Castelló, E., and J. C. i Bernad. 2020. “Shellfish Consumption in the Early Upper Palaeolithic on the Mediterranean Coast of the Iberian Peninsula: The Example of Foradada Cave.” *Journal of Archaeological Science: Reports* 29:102035.
- Wall-Scheffler, C. M. 2007. “Digital Cementum Luminance Analysis and the Haua Fteah Hominins: How Seasonality and Season of Use Changed through Time\*.” *Archaeometry* 49 (4): 815–826. <https://doi.org/10.1111/j.1475-4754.2007.00342.x>.
- Wanamaker, A. D., Jr., K. J. Kreutz, T. Wilson, H. W. Borns Jr., D. S. Introne, and S. Feindel. 2008. “Experimentally Determined Mg/Ca and Sr/Ca Ratios in Juvenile Bivalve Calcite for *Mytilus edulis*: Implications for Paleotemperature Reconstructions.” *Geo-Marine Letters* 28 (5-6): 359–368. <https://doi.org/10.1007/s00367-008-0112-8>.
- Zilhão, J., D. E. Angelucci, E. Badal-García, F. d’Errico, F. Daniel, L. Dayet, K. Douka, et al. 2010. “Symbolic use of Marine Shells and Mineral Pigments by Iberian Neandertals.” *Proceedings of the National Academy of Sciences* 107 (3): 1023–1028. <https://doi.org/10.1073/pnas.0914088107>.