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RESEARCH

Marine resource exploitation and human settlement patterns during the Neolithic in SW Europe: stable oxygen isotope analyses ($\delta^{18}O$) on *Phorcus lineatus* (da Costa, 1778) from Campo de Hockey (San Fernando, Cádiz, Spain)

Asier García-Escárzaga[1,2] · Juan J. Cantillo-Duarte[3] · Stefania Milano[4,5] · Rosa Arniz-Mateos[6] · Igor Gutiérrez-Zugasti[6] · Enrique González-Ortegón[7] · Jose M. Corona-Borrego[3] · José Ramos-Muñoz[3] · André C. Colonese[1] · Eduardo Vijande-Vila[3]

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Abstract

In recent decades, investigations in the southern Iberian Peninsula have increased our understanding of the socio-economic impact of the spread of the Neolithic in southwestern Europe, including changes in marine resources exploitation. Nevertheless, considerable uncertainty still exists around the seasonality of such subsistence systems and the putative role of marine fish and shellfish to the evolving agro-pastoral economies. Earlier studies on the European Atlantic coast (including Iberia) have shown that the stable oxygen isotope ($\delta^{18}O$) values from the topshell *Phorcus lineatus* (da Costa, 1778) can be reliably used to derive seasonal sea surface temperatures (SST) during its lifespan. This information can be used by archaeologists to estimate the seasonality of mollusc collection in the past, and to shed light into settlement and subsistence patterns. This paper presents the results of a stable isotope study on archaeological shells of *P. lineatus* recovered from the Neolithic settlement of Campo de Hockey (Cádiz, Spain). We analysed shells from both funerary and residential contexts and found that *P. lineatus* was consumed year-round, but with a stronger preference during winter. Our results therefore contribute to advance our understanding of the role of coastal environments in early farming societies of southwestern Europe.

Keywords Bay of Cádiz · Shellfish resources · Subsistence strategies · Seasonality · Necropolis · Grave goods

✉ Asier García-Escárzaga
a.garcia.escarzaga@gmail.com; asier.garcia@uab.cat

1 Department of Prehistory and Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, Bellaterra, Spain

2 Department of Archaeology, Max Planck Institute for Geoanthropology (MPI-GEA), Jena, Germany

3 Department of History, Geography and Philosophy and University Institute of Marine Research (INMAR), Universidad de Cádiz, Cádiz, Spain

4 Thermo Fisher Scientific GmbH, Bremen, Germany

5 Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology (MPI-EVA), Leipzig, Germany

6 Instituto Internacional de Investigaciones Prehistóricas de Cantabria (Universidad de Cantabria, Gobierno de Cantabria, Banco Santander), Santander, Spain

7 Instituto de Ciencias Marinas de Andalucía (ICMAN-CSIC), Puerto Real, Cadiz, Spain

Introduction

The Neolithic of the south of the Iberian Peninsula is divided into three periods: Early Neolithic (6000–4900 cal BC), Middle Neolithic (5000/4900–4300/4200 cal BC), and Late Neolithic (4300/4200–3400/3300 cal BC) (Molina-González et al. 2012). The settlement of Campo de Hockey straddles the late stages of the Middle Neolithic and the beginning of the Late Neolithic. This period witnessed significant transformations in terms of both subsistence strategies and settlement patterns, including the earliest permanent settlements, which are linked to the intensification of livestock and agricultural production. This led to the formalisation of land ownership and the construction of surplus storage facilities (silos, wells, etc.). The collective-based model of earlier periods, represented in the Bay of Cádiz by the site of El Retamar (Ramos-Muñoz and Lazarich-González 2002), came to an end in the late 5th millennium BC.

Semi-sedentary groups whose way of life resembled that of the last hunter-gatherers (with the tentative addition of herding and agricultural practices) were replaced by the first stable settlements, in which animal husbandry and crop cultivation played a much more important economic role. These economic practices intensified during the 4th millennium BC, with the emergence of so-called “silo fields,” represented in the Bay of Cádiz by the sites of Cantarranas-Las Viñas (Ruiz-Gil and Ruiz-Mata 1999), La Esparragosa (Vijande-Vila et al. 2019), Set Parralejos (Villalpando and Montañés 2009), and El Trobal (Martínez-Romero 2022).

Several questions concerning the subsistence strategies of these groups remain to be answered, including which occupation model was adopted in the so-called “pit-settlements” or how marine resources were exploited. The permanent or seasonal nature of these settlements is a matter of debate (Márquez-Romero 2001; Lucena and Martínez 2004; Nocete 2014), and considering the heterogeneity of the settlements included in this category, each site should be analysed individually. On the other hand, according to some researchers, the adoption of typically neolithic economy led to a reduction in the intake of marine proteins (Cubas et al. 2019; Salazar-Garcia et al. 2017). However, other studies argued for continuity in mollusc exploitation practices (Cantillo-Duarte 2019; Pascual-Benito 2014). Although our knowledge about the relationship between humans and coastal resources in the southern Iberian Peninsula during the Neolithic has notably increased in recent decades, mainly regarding the species consumed and their collection areas (Cantillo-Duarte 2012, 2019), some aspects, with far-reaching implications to reconstruct the way of life of the earliest farmers remain unknown. Determining the seasonality of marine exploitation, for example, can expand our understanding of the diversity of subsistence and settlement strategies in this region (Andrus 2011; García-Escárzaga 2020; Leng and Lewis 2016; Thomas 2015).

Archaeological shell remains can provide valuable information on coastal exploitation patterns. The stable oxygen isotope ($\delta^{18}O$) values derived from shell calcium carbonate reflect seawater environmental conditions (mainly temperature) during the mollusc’s life span (Bailey et al. 1983; Gröcke and Gillikin 2008; Owen et al. 2008; Wanamaker et al. 2007). This approach has been extensively used to determine the season(s) when molluscs were collected by past human societies (Burchell et al. 2018; Branscombe et al. 2021; García-Escárzaga et al. 2019a; Leclerc et al. 2023; Prendergast et al. 2016). However, the methodology needs to be tested on modern populations before it can be applied to archaeological specimens, essentially to confirm that shell oxygen isotope composition reliably records the seawater temperature variations during the mollusc’s life and that shell growth stoppages (if any) are no longer than a season (i.e., three months).

Previous studies in northern Iberian Peninsula and southern Britain using modern specimens have shown that the stable oxygen isotope composition ($\delta^{18}O$) of the shell of *Phorcus lineatus* (da Costa, 1778), a widely exploited species in prehistoric Europe, reflect the seawater temperatures during the shell formation (García-Escárzaga et al. 2019b; Gutiérrez-Zugasti et al. 2015; Mannino et al. 2003; Mannino and Thomas 2007). Although previous sclerochronological analysis conducted using modern specimens from northern Iberian Peninsula revealed older specimens of this species occasionally stopped their growth during a few weeks (García-Escárzaga et al. 2019b) and the seawater temperatures in Cádiz are ca. 2 ºC higher, longer summer growth stoppages are not expected. The stable isotopes of oxygen $\delta^{18}O$ analyses undertaken on modern *Phorcus turbinatus* (Born, 1778) shells collected from different Mediterranean locations showed that growth patterns in this taxon do not significantly change despite the higher summer water temperatures (2 °C) in southern and warmer locations compared with those recorded in the northern Mediterranean coasts (Colonese et al. 2009; Mannino et al. 2008; Prendergast et al. 2013). This strongly suggests that *Phorcus* genus can adapt to local environmental conditions without changes in growth patterns, if temperature variations are not significant.

In this investigation, $\delta^{18}O$ analyses on shells of *P. lineatus* recovered at the Neolithic site of Campo de Hockey (Andalusia, Spain) were carried out to determine seasonality in marine resources collection during the Neolithic in southwestern Europe. The results allow us to reconstruct the seasonal strategies employed by neolithic groups that occupied Campo de Hockey and to establish whether this island site was occupied all year round or seasonally. This study contributes to the long-standing debate on the role of marine resources during the spread and establishment of farming in southwestern Europe.

Campo de hockey site

The Neolithic settlement of Campo de Hockey (San Fernando, Cádiz) is situated in the Bay of Cádiz, at the southernmost tip of the Iberian Peninsula. This site was on an island during the Middle Holocene (Arteaga et al. 2008; Alonso et al. 2009). The settlement was at 12–18 m.a.s.l. and approximately 150 m from the ancient coastline. Although the economy of the community largely relied on herding and agriculture, the exploitation of marine resources was also important, as suggested by the number and diversity of mollusc shell and fish bone remains found at the site (Vijande-Vila 2009; Cantillo-Duarte and Vijande-Vila 2014). To date, two excavation seasons have been undertaken. The first, in 2007–2008, was motivated by the construction of a hockey pitch (Campo de Hockey 1) (Fig. 1). The excavation affected 12,000 m^2 and led

Fig. 1 Location of Campo de Hockey site in southern Iberian Peninsula. The red line above marks the estimated location of the coastline during the Neolithic. The yellow rectangle indicates the location of the first excavation (2007–2008) and the red rectangle indicates the second excavation (2018)

to the discovery of domestic structures (sunken huts), storage facilities (well-silos), and an extensive necropolis with 53 tombs (Vijande-Vila et al. 2015, 2022). The second excavation season took place in 2018 (Campo de Hockey 2) and was triggered by the construction of a housing estate (Fig. 1). This excavation affected 1573 m^2 to the west of Campo de Hockey 1, and 28 archaeological assemblages were attested, including seventeen hearths, two shell middens, four tombs, and five rock clusters. The large number of hearths and the middens suggest that the area was used to process and consume marine resources.

The two excavation seasons led to the recovery of 12,579 malacological remains, totalling a minimal number of individuals (MNI) of 2885. Shell remains were mostly represented by *P. lineatus* (832 MNI; 28.83%), followed by *Ruditapes decussatus* (Linnaeus, 1758) (724 MNI; 25.09%), *Solen marginatus* Pulteney, 1799 (684 MNI; 23.70%), and *Hexaplex trunculus* (Linnaeus, 1758) (184 MNI; 6.33%).

All these species were likely collected for food, but some fragments of *R. decussatus* may have been also used as tools (Cuenca-Solana 2015; Cuenca-Solana et al. 2011) and other gastropods as personal adornments (Cantillo-Duarte 2019). A total of 341 fish remains, belonging to six taxa, were also identified.

Absolute dates from Campo de Hockey 1 suggest that the site was inhabited for around 300 years, with two overlapping phases, according to the Bayesian model applied to the nineteen radiocarbon dates available (Vijande-Vila et al. 2022). Phase I ranged from 4050–3960 to 3985–3900 cal BC (0–100-year span), and phase II from 3990–3755 to 3895–3620 cal BC (0–215-year span), indicating continuous occupation over 300 years and several generations. Tomb E3T15 is perhaps somewhat earlier, dating to 4335–4060 cal BC (Vijande-Vila et al. 2022). In addition, two new radiocarbon dates from the two shell middens (stratigraphic units 142 and 66) documented at the Campo de Hockey 2 site (Table 1) indicate that both contexts belong to phases I and II, respectively (Fig. 2).

Materials and methods

Shell remains analysed

A total of 49 shells recovered from six different stratigraphic units (SU) were analysed for their sequential $\delta^{18}O$ values (Table 2). Two of these units (SU 66 and SU 142) are shell midden deposits, and the other four are human funerary structures (Fig. 3).

SU 66 (feature code: 13) (Fig. 3A) is a shell midden located in a pit found in Campo de Hockey 2; it is 2.51 m^2 in size and includes malacological and ichthyological remains and, to a lesser extent, land fauna, stone tools, and ceramics. A shell was radiocarbon dated to 3960–3630 cal BC (Vijande-Vila et al. 2023).

SU 142 (feature code: 36) (Fig. 3B) is a shell midden located in Campo de Hockey 2; it is 3.13 m^2 in size and mostly comprises malacological and ichthyological remains and some land fauna, stone tools, and ceramics. A shell was radiocarbon dated to 4250–3865 cal BC (Vijande-Vila et al. 2023).

SU 1406 (feature code: E11T14) (Fig. 3C) is a proto-megalithic burial with a circular pit, 2 m in diameter, dug into the geological substratum. The funerary chamber is covered by a mound formed by superposed large stone slabs. Two adult males buried at different times were found inside the tomb (the most monumental in the necropolis) alongside prestigious grave goods. The large number of fragments of *P. lineatus* found inside the tomb is also of note. Two radiocarbon dates are available: one from a shell (*Phorcus lineatus*) dated to 4036–3669 cal BC and another from human remains (Individual 16), dated to 4060–3950 cal BC (Vijande-Vila et al. 2022; Sánchez-Barba et al. 2019).

SU 1704 (feature code: E3T17) (Fig. 3D) is a burial in a simple oval pit containing an adult male in foetal position and no grave goods. The bone sample from this individual yielded a radiocarbon age of 3970–3800 cal BC (Vijande-Vila et al. 2022).

SU 705 (feature code: E7T7) (Fig. 3E) is a protomegalithic burial with a polygonal funerary chamber dug into the ground and outlined by six large stone slabs (orthostates). Inside, a male adult was in the foetal position, and no grave goods were found. A sample of *Bolinus brandaris* (Linnaeus, 1758) was radiocarbon dated to 4060–3665 cal BC (Vijande-Vila et al. 2022).

The SU 1516 (structure code: E10T15) (Fig. 3F) is a double burial in a simple pit dug into the geological substratum. Two individuals have been documented in an embracing position with their lower and upper body extremities intertwined. It highlights the presence of red pigment (ochre of hematite origin) in the lower half of both individuals (Vijande-Vila et al. 2015). We have radiocarbon dated a human bone, reporting a chronology of 3948–3708 cal BC (Vijande-Vila 2009).

Calcium carbonate sampling and stable oxygen isotope analyses

Shells of *P. lineatus* were first treated with 30 vol% H_2O_2 for 48 h to remove organic matter following a well-established and widely published methodology (Colonese et al. 2009; García-Escárzaga et al. 2019a, 2019b; Gutiérrez-Zugasti et al. 2015). The clean shells were then air-dried at room

Table 1 AMS radiocarbon dates for the two shell middens excavated in Campo de Hockey II. ^{14}C ages were calibrated using the IntCal20 (Reimer et al. 2020) and Marine20 (Heaton et al. 2020) calibration curves and Oxcal 4.4 calibration program (Bronk Ramsey 2009a). The reservoir effect was corrected using a ΔR value of 32.63 ± 33.27, estimated by Vijande-Vila et al. (2022) from IsoMemoApp Database (Fernandes et al. 2020)

Lab. code	Date BP	Interval Cal BC (2σ)	Material	Species	Structure	Stratrigraphic unit (SU)	Reference
BETA-526877	5820 ± 30	4250–3865	Shell	*Phorcus lineatus*	EST.36	142	Vijande-Vila et al. 2023
BETA-522086	5590 ± 30	3960–3630	Shell	*Phorcus lineatus*	EST.13	66	Vijande-Vila et al. 2023

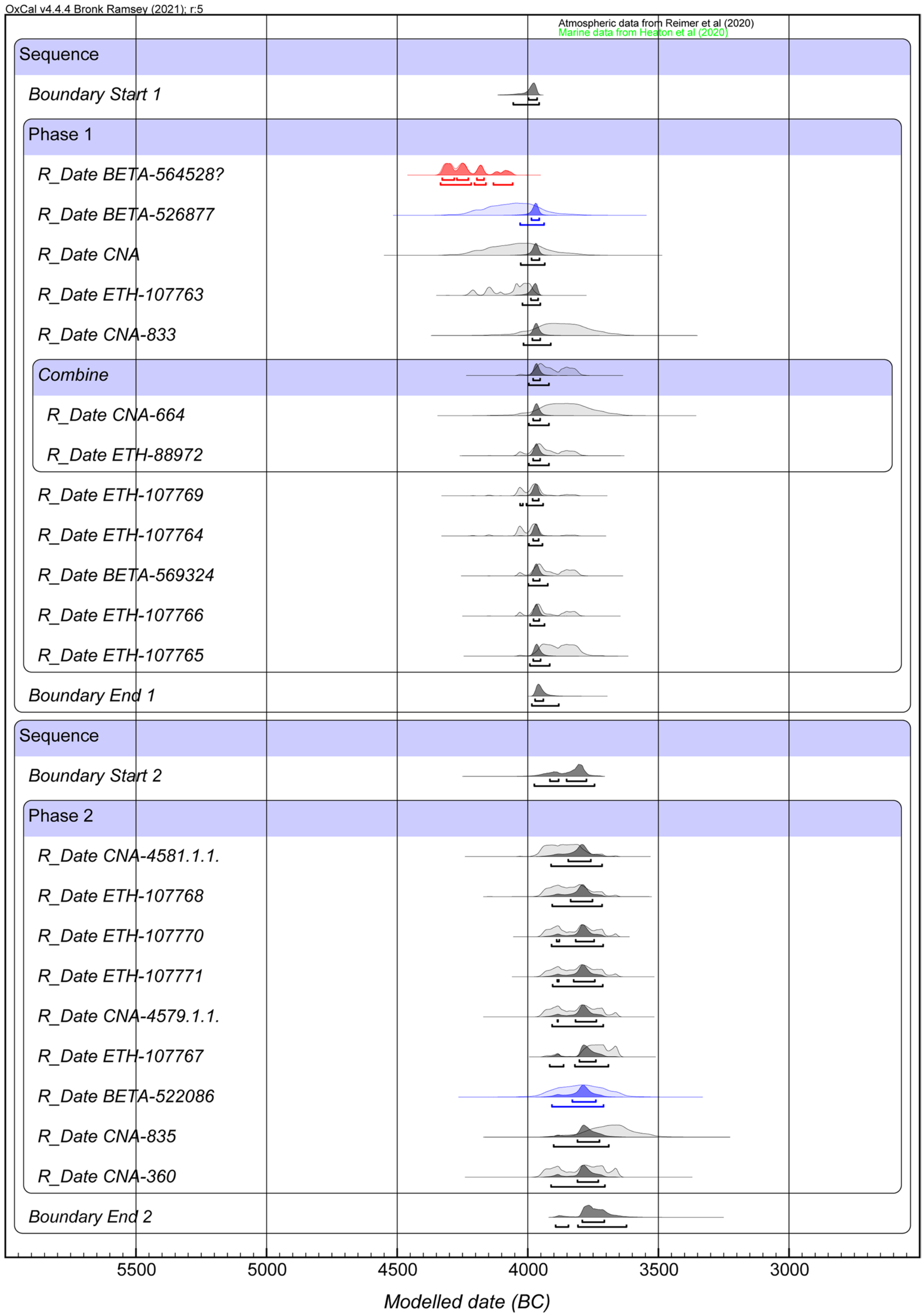

Fig. 2 Bayesian modelling of radiocarbon dates obtained from Campo de Hockey I and II (Vijande-Vila et al. 2022; Table 1) calibrated in OxCal v.4.4.2 (Bronk Ramsey 2009a, 2009b) using IntCal20 (Reimer et al. 2020) and Marine20 (Heaton et al. 2020) curves and the ΔR value previously estimated by Vijande-Vila et al. (2022) for this area from IsoMemoApp Database (Fernandes et al. 2020). The OxCal model code used herein was developed by Vijande-Vila et al. (2022). The red colour indicates an outlier detected by Vijande-Vila et al. (2022), and the blue colour is used to highlight the two radiocarbon dates obtained from the shell middens discovered at the Campo de Hockey 2

Table 2 Provenance and ID codes of shell samples analysed in this study

Archaeological site	Stratigraphic unit (SU)	Archaeological assemblage	Number of shells analysed	Shell ID codes
Campo de Hockey II	66	Shell midden	11	CH.66.1 to CH.66.11
Campo de Hockey II	142	Shell midden	11	CH.142.1 to CH.142.11
Campo de Hockey I	1406	Burial	12	CH.1406.1 to CH.1406.12
Campo de Hockey I	1704	Burial	7	CH.1704.1 to CH.1704.7
Campo de Hockey I	705	Burial	5	CH.705.1 to CH.705.5
Campo de Hockey I	1516	Burial	3	CH.1516.1 to CH.1516.3

temperature. According to the dataset previously published for this species, *P. lineatus* has an outer calcitic shell layer and an inner aragonitic layer (Gutiérrez-Zugasti et al. 2015; Mannino and Thomas 2007; Mannino et al. 2003). Carbonate micro-samples were taken from the aragonite layer using a dentist microdrill with a 0.5-mm tungsten drill bit. Before removing the outer calcite layer to access the inner aragonite layer using a Dremmel microdrill and a 2-mm diamond drill bit, a calcium carbonate micro-sample was taken from the inner part of the shell lip (Fig. 4a) to prevent thus losing the last shell growth in the case the shell edge would break when outer calcite layer removal. The remaining micro-samples were sequentially taken from the shell edge to the apex along the whorl at 1-mm intervals (Fig. 4b). For the sake of

Fig. 3 Stratigraphic units (SU) from which *P. lineatus* shells analysed in this investigation were recovered: SU 66 (**A**), SU 142 (**B**), SU 1406 (**C**), SU 1704 (**D**), SU 705 (**E**) and SU 1516 (**F**)

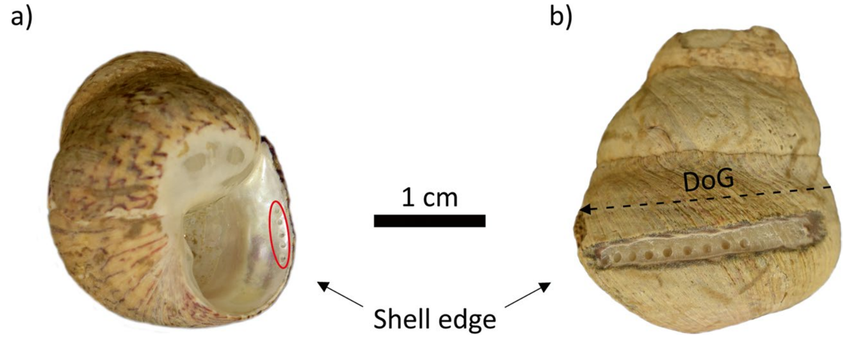

Fig. 4 Methodology used for extracting calcium carbonate micro-samples from the aragonite layer on *P. lineatus* shells. **a)** First $CaCO_3$ micro-sample was taken from the inner part of the shell edge, and **b)** additional micro-samples were sequentially taken from the shell edge to the apex following the direction of growth (DoG)

comparison, the micro-sampling method used reproduces that deployed in previous studies of this species (García-Escárzaga et al. 2019a, 2022; Gutiérrez-Zugasti et al. 2015; Mannino et al., 2003; Mannino and Thomas, 2007), as well as of other species of the same genus (Colonese et al. 2009, 2018; Mannino et al. 2007, 2008, 2011, 2014; Prendergast et al. 2013, 2016).

In three shells (CH.66.1, CH.142.1, and CH.1406.1), between 67 and 83 carbonate micro-samples were taken from the shell edge to obtain long sequential isotope series. In the remaining shells ($n = 46$), ten calcium carbonate micro-samples were taken from the shell edge. This led to a total of 680 calcium carbonate micro-samples. Micro-samples (ranging between 150 and 200 μg) were stored within glass vials (1.5 ml) until they were analysed.

Carbonate micro-samples were analysed using two isotope ratio mass spectrometers (IRMS). A ThermoFisher MAT 253 gas IRMS coupled to Kiel IV automated carbonate preparation device at the Max Planck Institute for Evolutionary Anthropology (MPI-EVA) was used to analyse micro-samples taken from shells recovered from SU 705, 1406, 1516, and shell midden 142, as well as the specimen sequentially sampled from shell midden 66 (N of micro-samples = 510). The average precision error (1σ; computed from eight measurements per sample) was better than 0.23‰ for $\delta^{18}O$, and the long-term accuracy based on blindly measured IAEA-603 micro-samples (N = 58) was better than 0.14‰ for $\delta^{18}O$. Additionally, an IRMS Thermo Scientific DELTA V coupled to a Gas Bench II Interface at the University of Burgos (UBU) was used to measure the oxygen isotopic composition of micro-samples taken from shells recovered from SU 1704 and the remaining individuals from shell midden 66 (N of micro-samples = 170). The raw isotopic ratios were normalized against NBS-18 (−23.2‰), IAEA-603 (−2.37‰), and IAEA-CO-8 (−22.7‰) standards. The analytical error of the instrument was systematically better than 0.1‰, as determined by repeated measurement of an in-house MERCK. In both instances, the results were reported in per mil (‰) relative to the Vienna Pee-Dee Belemnite (VPDB) standard.

Season of collection estimation

To establish the seasons in which *P. lineatus* specimens were harvested, the quartile system proposed by (Mannino et al. 2003, Mannino and Thomas 2007) and applied in multiple successful studies (Colonese et al. 2009, 2018; García-Escárzaga et al. 2019a; Kimball et al. 2009; Prendergast et al. 2016) was adopted. Briefly, the four equal quartiles into which the isotopic range can be divided reflect the temperatures experienced by the molluscs during winter (= upper quartile), summer (= lower quartile), and spring and autumn (= two intermediate quartiles). According to this, the isotopic value of the last shell growth, which represents the season in which the mollusc was harvested, can be assigned to one quartile. Concerning values assigned to intermediate quartiles, a collection in autumn or spring can be distinguished by considering the general tendency of the series during the final months of the mollusc's life (warming = spring; cooling = autumn). Finally, to determine the intra-annual $\delta^{18}O$ range, and the maximum and minimum $\delta^{18}O$ values used to infer the season in which the shells were collected, a combination of $\delta^{18}O$ values from both the long and short isotope sequences obtained from shells recovered from all six stratigraphic units were employed.

Results

Stable oxygen isotope values

The $\delta^{18}O$ values obtained from 680 micro-samples of calcium carbonate ranged from + 2.36 to − 0.72‰ (Table 3). The maximum and minimum $\delta^{18}O$ values obtained from all the shell analysed were used to establish the range of $\delta^{18}O$ values expected for this chronology and, therefore, to estimate the four isotope quartiles (Table 3).

Sequential $\delta^{18}O$ values followed a sinusoidal pattern along the shell growth axis. The time span represented by the $\delta^{18}O$ values was variable, ranging from a few months to more than 1 year in the case of the short series

Table 3 Maxima and minima $\delta^{18}O$ values from short and long sequences for each stratigraphic unit (SU). Intra-annual $\delta^{18}O$ range of each SU was estimated using the maximum and minimum values obtained from that SU. The four quartiles were estimated from the intra-annual $\delta^{18}O$ range

Stratigraphic units (SU)	Maximum $\delta^{18}O$ value	Minimum $\delta^{18}O$ value	Intra-annual $\delta^{18}O$ range	1st quartile (winter)	2nd and 3rd quartiles	4th quartile (Summer)
66	+2.36	−0.72	+3.07			
142	+2.25	−0.66	+2.91			
1406	+2.24	−0.72	+2.96			
1704	+2.18	−0.71	+2.89			
705	+1.89	−0.35	+2.25			
1516	+2.34	−0.61	+2.96			
Total SU	+2.36	−0.72	+3.07	+2.36 – +1.59	+1.58 – +0.06	+0.05 – −0.72

(Supplementary Figs. 1–6), and from 4 to 5 years in the three long series (Supplementary Fig. 7).

The season(s) of collection

Shell edge $\delta^{18}O$ values, which are representative of the last growth of the specimens, indicate that *P. lineatus* was collected throughout the year (Fig. 5a), but with a strong preference for winter (N = 21; 42.9%), followed by autumn (N = 20; 40.8%), spring (N = 6; 12.2%), and summer months (N = 2; 4.1%). Concerning shell harvested in autumn and spring, 56% of shells yielded shell edge values ascribed to the upper third of the intermediate quartiles (= $\delta^{18}O$ value > 1.07‰), indicating that these molluscs were collected in late autumn and early spring. In conclusion, 73.5% of the shells recovered from Campo de Hockey were collected during the colder months of the year (ca. from November to April).

The analysed specimens from the six stratigraphic units led to similar conclusions. In all contexts, most animals (between 54.5 and 90.9%) were collected from late autumn to early spring. However, while values from specimens in shell midden 66 indicated a year-round exploitation (Fig. 5b), samples from the shell midden 142 were mostly harvested in winter and none were harvested in summer (Fig. 5c). Similar differences were also be observed between funerary contexts (Fig. 5d–g). Interestingly, all four seasons are represented in SU 1406, in which two individuals were deposited. Only two and three seasons were recorded in the shells recovered from SU 1704 and 705, in which single individuals were buried.

Discussion

Shells and human burials

The presence of marine shells in human burials has been documented from at least the Upper Palaeolithic (Vanhaeren and d'Errico 2005), although the evidence for more recent periods is much more abundant (Arias and Garralda 1996; Cristiani et al. 2021; Gibaja 2004). Nevertheless, determining whether the shells were intentionally used as grave goods or accidentally introduced from residential layers into which graves were dug remains a matter of debate (Gutiérrez-Zugasti and Cuenca-Solana 2015). Data concerning seasonality can help to address this issue.

The number of mollusc collection seasons represented in three out of four burials was higher than the number of human individuals recovered from them (Fig. 5d–f). Four seasons have been deduced for the SU 1406 (Fig. 5d), and only two individuals have been documented. Similarly, three and two seasons are represented in SU 1704 (Fig. 5e) and 705 (Fig. 5f), but only one human body was documented in both. Only in SU 1516 did the number of buried bodies and harvest seasons of *P. lineatus* match (Fig. 5g). However, the evidence suggests that these two individuals were buried at the same time (Vijande-Vila 2009; Vijande-Vila et al. 2015), so no correlation between the funerary rituals and the season in which molluscs were collected could be established. This allows us to conclude that the shells of *P. lineatus* were not part of the funerary rituals and should not be regarded as a grave good. Molluscs were probably consumed previously, and shells were discarded in areas where humans were buried later. This agrees with the fact that the shells appear mixed into the sedimentary fill, and they were not intentionally deposited. In any case, it is unlikely that a particularly long-time interval separated both events because no statistical differences between radiocarbon dates from human bones and marine shells were found (Vijande-Vila et al. 2022).

Seasonal exploitation of *P. lineatus*

The development of farming and its spread across Europe had profound implications for human behaviour and subsistence strategies in the region. How these changes impacted the relationship between human groups and coastal environments and the shellfish exploitation patterns still needs

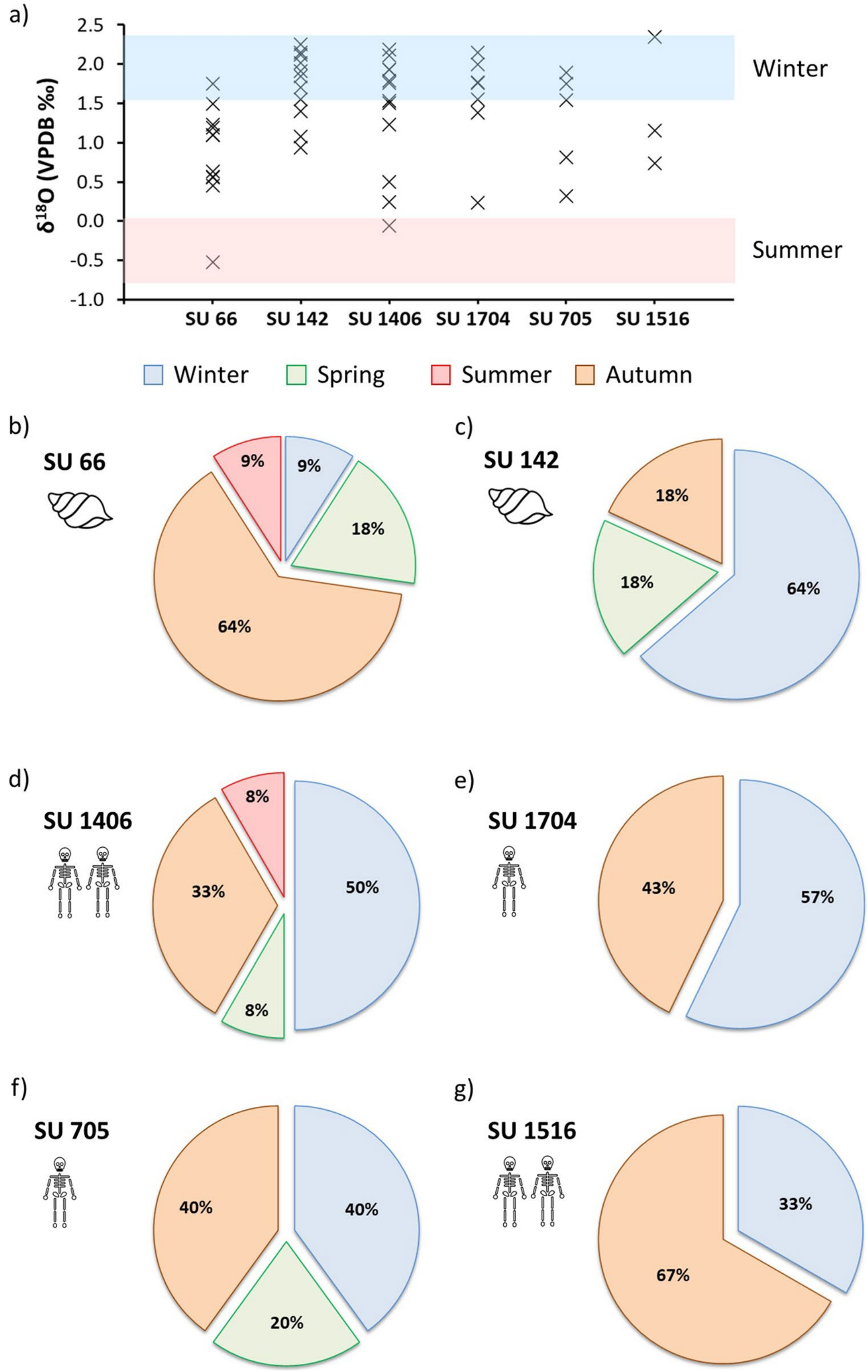

Fig. 5 **a)** Position of shell-edge $\delta^{18}O$ values from every shell in relation to the expected intra-annual range for the Middle Holocene (each cross represents the last $\delta^{18}O$ values of one specimen, and the blue and red rectangles represent the winter and summer quartiles, respectively), and **b** to **g)** percentage of samples assigned to each season in the six stratigraphic units (SU) from which the shells analysed were recovered. The shell sign indicates that the SU corresponds to a shell midden, and the human skeleton sign indicates that the SU corresponds to a human burial. The number of skeleton(s) specifies the number of individuals found in the tombs

to be clarified. Coastal resources played an important role for Mesolithic populations in Atlantic Europe and around the Mediterranean (Cubas et al. 2019; Fontanals-Coll et al. 2023; García-Escárzaga and Gutiérrez-Zugasti 2021). Previous studies on Iberian paleodiets based on carbon and nitrogen stable isotope analyses reported a significant decrease in the consumption of marine proteins during the Neolithic (Fontanals-Coll et al. 2015; Salazar-García et al. 2017; Cubas et al. 2019). In contrast, archaeomalacological evidence attests to significant shell assemblages, suggesting that this food source continued to be a staple for early farmers (Álvarez-Fernández et al. 2022; Cantillo-Duarte 2019; Pascual-Benito 2014). However, most attempts to establish whether the new economic strategies triggered changes in coastal resource exploitation have adopted a quantitative perspective, especially concerning how much molluscs contributed to the human diet and a new qualitative perspective must also be considered. Recent investigations have demonstrated that the last foragers employed mollusc collection strategies to maximise their energetic returns (García-Escárzaga et al. 2019a). It is unclear whether similar strategies were employed by farming groups that presumably relied less on wild resources.

The results from this study suggest that the earliest farmers in the southern Iberian Peninsula primarily consumed *P. lineatus* during the colder months, with 73.5% of specimens collected between late autumn and early spring. This seasonal pattern is similar to that detected in other Mesolithic sites in the European Atlantic façade, including northern Iberian Peninsula (Deith and Shackleton 1986; García-Escárzaga et al. 2019a; Mannino et al. 2003), as well as in the Mediterranean basin (Branscombe et al. 2021; Colonese et al. 2018; Mannino et al. 2008, 2014; Prendergast et al. 2016). We suspect that such a foraging model was likely driven by the higher mollusc meat-yield return during colder months (García-Escárzaga et al. 2019a). If so, this would imply that Neolithic intertidal exploitation was also governed by cost–benefit principles, regardless of the effective contribution of marine proteins to diet.

Human settlement patterns in Campo de Hockey

Recent studies in the province of Cádiz and elsewhere in the southwest Iberian Peninsula have contributed to unseating the so-called “Cave Neolithic” paradigm (Navarrete-Enciso 1976; Pellicer and Acosta 1982, 1986). This research has attested to a widespread pattern of open-air sites near the coast (Ramos-Muñoz et al. 2013a) and inland locations (Ramos-Muñoz et al. 2013b). These sites are generally close to water sources, agriculture-friendly soils (CEBAC 1963), and maritime resources (Cantillo-Duarte et al. 2010; Ramos-Muñoz et al. 2011; Cantillo-Duarte and Vijande-Vila 2014; Clemente-Conte et al. 2020). In this sense, Campo de Hockey is a typical example of an open-air neolithic site in the Bay of Cádiz. Geoarchaeological analysis has demonstrated that modern San Fernando was previously an island (Arteaga et al. 2008; Alonso et al. 2009), and more Neolithic settlements have been found in it (Ramos-Muñoz et al. 2006). Mainland sites, such as El Retamar (Ramos-Muñoz and Lazarich-González 2002), and La Esparragosa (Vijande-Vila et al. 2019) were also near the coast.

It has been shown that agricultural practices did not consolidate in these open-air sites until late in the fifth millennium BC (Molina-González et al. 2012) and that locally existing economic practices such as hunting, fishing, and shellfish harvesting continued during the Neolithic. As such, these human groups practised a wide variety of economic activities and targeted a broad spectrum of resources (Arteaga and Roos 2009; Pérez-Rodríguez 2005; Ramos-Muñoz et al. 2006; Uzquiano et al. 2021). In addition, they were part of extensive trade networks of stone objects (Domínguez-Bella et al. 2016) and exotic goods (Domínguez-Bella et al. 2008). These open-air sites, dated to the late fifth and the fourth millennium BC, present features typical of tribal communities, with domestic and storage areas, represented by silo fields, as well as areas for producing stone tools (Vijande-Vila et al. 2019; Villalpando and Montañés 2016; Cantillo-Duarte et al. 2017). Similar settlement patterns are found in the Algarve and the area of Setúbal-Lisbon, on the Atlantic coast of Portugal (Soares 2013; Carvalho 2018), where they closely reproduce the settlement patterns of the last hunter-gatherer communities, recognisable by their characteristic shell middens (Bicho et al. 2013; Gabriel et al. 2022). Similar patterns are also found in Atlantic Brittany, where, interestingly, some of these sites are related to salt production (Cassen et al. 2008; Cassen and Weller 2013), and sea resources played an important economic role; their adoption of herding and agricultural practices was very gradual. However, information on whether these open-air sites were seasonally inhabited or, contrarily, occupied year-round still needs to be discovered.

The evidence from Campo de Hockey has allowed us to consider the site as a permanent human settlement (Vijande-Vila 2009; Vijande-Vila et al. 2015). The economic activities and the residential features, particularly the large necropolis, which represents the beginning of funerary Megalithism in the Iberian Peninsula, suggest non-seasonal settlement (Vijande-Vila et al. 2022). However, new datasets were still needed to confirm this hypothesis from empirical proxies. The results from seasonal collection patterns deduced from short and long isotope profiles revealed that *P. lineatus* was mainly collected from November to April. However, harvesting, although less intensive, was carried out also during the warmer months (i.e., from late spring to early autumn) (Fig. 5), thus supporting the hypothesis that Campo de Hockey was inhabited year-round. This conclusion has important implications for increasing our understanding of settlement patterns developed by the earliest farming populations in southwestern coastal Europe. However, further investigations using remains recovered from previously unstudied archaeological sites are still required to improve our knowledge from a local to a regional perspective.

Conclusions

This study applied stable oxygen isotope analyses on archaeological shells of *P. lineatus* from the Neolithic site of Campo de Hockey. The results have emphasised the value of this methodological approach as a proxy to infer several uncertain issues of past human behaviour. These reveal that, contrary to previous assumptions, shells found in funerary contexts were not intentionally deposited as grave goods. Rather, these had been likely introduced as part of the sediment used to cover the human burials. The results also indicate that neolithic communities predominantly consumed *P. lineatus* during the colder months of the year, aligning with the broader patterns of shellfish exploitation in prehistoric times in Atlantic and Mediterranean Europe. Seasonal shellfish collection was possibly driven by the high energetic return observed in intertidal molluscs during winter compared to summer months. This conclusion is crucial as it strongly suggests that patterns of littoral resource exploitation were not significantly altered by the Neolithic way of life, contrary to earlier theories. Finally, while *P. lineatus* was preferentially consumed during the colder months, in some contexts, it was collected throughout the year. This supports the hypothesis that the Campo de Hockey was inhabited year-round by farming groups, indicating their ability to develop permanent settlement in coastal enclaves, including small islands like the one where the site was situated in the early stages of the Middle Holocene.

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Author contributions We confirm that all authors have approved the final version of the manuscript and have made substantial contributions. EVV and JCB excavated Campo de Hockey. JCD and JRM carried out the archaeomalacological studies of shellfish remains recovered from Campo de Hockey. AGE, IGZ, and EVV designed the stable oxygen isotopic analysis. AGE and RAM extracted the calcium carbonate samples from *Phorcus lineatus* shells. SM conducted the stable oxygen isotope analysis at MPI-EVA. EGO provided information on the current environmental conditions in the Bay of Cádiz. All authors interpreted the data. All authors wrote and provided comments on the manuscript.

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Data Availability All isotopic data used in this study are included in the Supplementary Material.

Declarations

Competing interests The authors declare no competing interests.

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