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Jean-François Cudennec [a,*,1], Cynthia Oliveira [b,*,1], Pierre Stephan [c], Clément Nicolas [d], Yvan Pailler [e], Fabien Dewilde [f], Éric Dabas [g], Yves-Marie Paulet [g]

[a] University of Derby, College of Science and Engineering. Kedleston Road DE221GP, Derby, United Kingdom
[b] University of Western Brittany (UBO, Brest), UMR CNRS 6554 LETG and UMR CNRS 6539 LEMAR, Institut Universitaire Européen de la Mer, Rue Dumont d'Urville 29280, Plouzané, France
[c] CNRS, Univ Brest, Nantes Université, Université de Rennes, LETG, UMR 6554, F-29280, Plouzané, France
[d] National Center for Scientific Research (CNRS), UMR 8215 Trajectoires, Centre Malher, 9 Rue Malher 75004, Paris, France
[e] University of Western Brittany (UBO, Brest), UMR CNRS 6554 LETG, Institut Universitaire Européen de la Mer, Rue Dumont d'Urville 29280, Plouzané, France
[f] University of Western Brittany (UBO, Brest), UMS 3113, Pôle Spectrométrie Océan (PSO), Institut Universitaire Européen de la Mer, Rue Dumont d'Urville 29280, Plouzané, France
[g] University of Western Brittany (UBO, Brest), UMR CNRS 6539 LEMAR, Institut Universitaire Européen de la Mer, Rue Dumont d'Urville 29280, Plouzané, France

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ABSTRACT

The stable oxygen isotopes ratio ($\delta^{18}O$) from marine mollusk carbonated shells is widely used as a palaeothermometer, as the main driver of this ratio is the temperature (coupled with the salinity) at which the carbonate precipitated. This method is also used on anthropogenic shell middens, as a proxy for past human practices and their use of marine resources: the Sea-Surface Temperature reconstructed from the shell margin can be interpreted as the season during which the people who produced the midden collected the shells. To better understand the occupation patterns and protohistoric practices of shellfish collection in the Iroise Sea and the Molène archipelago (Finistère, France), we analyzed seasonality data of limpets (*Patella* sp.) from Late Neolithic (LN, 2570 – 2140 cal. BCE), Early Bronze Age (EBA, 2140 – 1740 cal. BCE) and Early Middle Age (EMA, 620 – 820 cal. CE) occupations within shell middens of two islands: Molène and Béniguet.

The methodology allowed us to discriminate seasonal and permanent occupations for Béniguet Island site, enriching archaeological observations. Our results also show that the largest shell middens yield all year round collection, on both islands, confirming the continuous occupation of these territories, despite uneven intensity of collection throughout the year. The most represented seasons are late winter and spring, both on Béniguet and Molène islands, and for LN and EBA suggesting an intensification of collection to compensate resource depletion toward the end of winter. These results complete and enhance the previous seasonality data existing on these sites demonstrating here that not only the number of analyzed shells but also their spatial distribution within the midden can impact the seasonality interpretation. This approach now needs to be completed by the determination of seasonality indicators on the other resources present in the middens, to truly grasp the domestic economies of these past insular populations.

1. Introduction

Shell middens are byproducts of human coastal settlements and understanding their composition, the species selection and the modalities of collection can provide helpful insights into the comprehension of the coastal populations' human-environment interaction and subsistence strategies (Álvarez et al., 2011; Gutiérrez-Zugasti et al., 2011). Among the different characteristics of each shell midden, the harvesting seasonality of their components is of particular interest. Intertidal and sedentary coastal mollusk species are available all year round when the

* Corresponding authors.
E-mail addresses: jf.cudennec@live.fr (J.-F. Cudennec), cynth.oliveira@gmail.com (C. Oliveira), yvan.pailler1@univ-brest.fr (Y. Pailler).
[1] Jean-François CUDENNEC and Cynthia OLIVEIRA are equal contributors to this work and designated as co-first authors.

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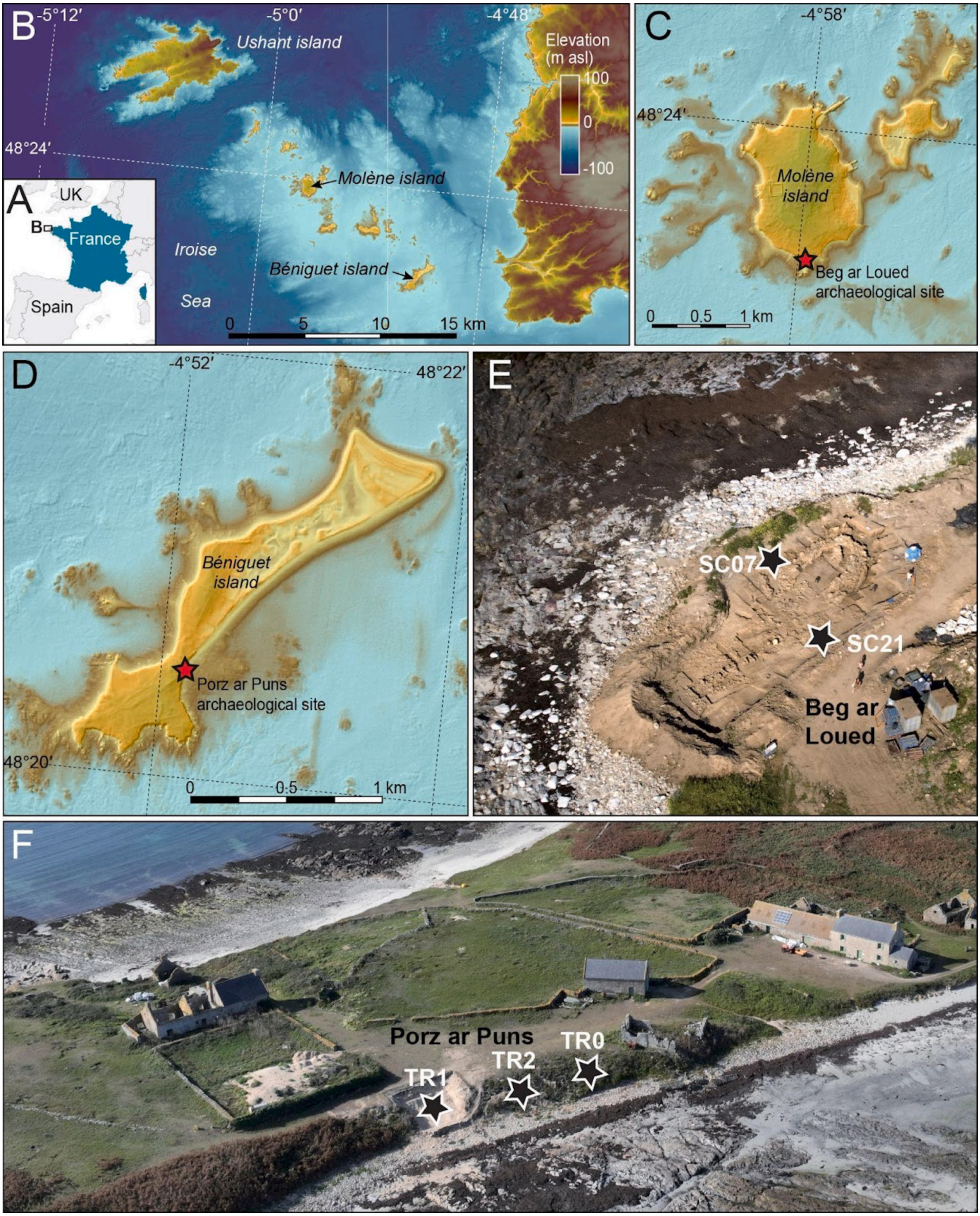

Fig. 1. Study sites. A and **B**: Location maps of the study area, the Molène Archipelago. **C** and **D**: Location maps of the archaeological sites of Beg ar Loued and Porz ar Puns on the islands of Molène and Béniguet, respectively. **E** and **F**: Aerial views of archaeological sites of Beg ar Loued (Molène island) and Porz ar Puns (Béniguet island), respectively. Red stars represent the archaeological sites. Black stars represent sampled pits (SC) and trenches (TR).

tide goes out, thus their collection (or the absence of it) indicates specific human behavior. By crossing archaeological observations with archeozoological data, it is therefore possible to infer some cultural preferences, group mobility and settlement occupation scheme.

Sclerochronology, the study of accretionary growth of skeletal materials (Andrus, 2011), is now widely used in archaeological context to access the environmental characteristics of the period, and can provide insight into different aspects of past human populations: harvesting seasonality, mobility and site occupation patterns (Hallmann et al., 2009; Burchell et al., 2014; Cannon & Burchell, 2017; Burchell et al., 2018; Loftus et al., 2019); evolution of practices through time and space (Andrus & Thompson, 2012); pressure on the shellfish's population (Mannino & Thomas, 2002) or shell middens constitution dynamic (Hausmann & Meredith-Williams, 2017).

In Brittany (France), Molène and Béniguet Islands, along with the rest of the Molene Archipelago, are positioned on a vast submerged plateau with an extended foreshore. The archaeological sites are in the heart of a marine ecosystem that still bears exceptional biomass and biodiversity today (Stéphan & Tissot, 2022). This environment has supported human communities since at least the Recent Neolithic (3300 cal. BCE onwards), as evidenced by numerous shell middens (Pailler & Nicolas, 2022), and our study sites constitute a unique case of a rich stratigraphy of occupations, spanning from the Final Neolithic to the Early Middle Ages.

The most common shellfish found in these middens are the limpet, *Patella* sp. (Mougne & Dupont, 2019). This genus (three species in Brittany nowadays) is still widely abundant in the nearby rocky shores, and there are still discussions about their identification based on the shell only. Today, *P. vulgata* is by far the most abundant of the three species on Molène archipelago rocky shores. The two other species, *P. ulyssiponensis* and *P. depressa*, are restricted to low shore, rock pools, or highly exposed area respectively (Stéphan & Tissot, 2022).

P. vulgata is an intertidal gastropod commonly found on rocky shores of cold- and warm-temperate regions of the eastern Atlantic. This species is notably resistant and can support salinities from 20 to 35 PSU (Practical Salinity Units) and temperatures between −8.7 and 42.8 °C (Crisp, 1965; Branch, 1981). The species is characterized by its homing behavior, where individuals reside on a specific "home scar" and venture out to graze on algae, diatoms, and spores (Schaal & Grall, 2015). Shell growth occurs mainly at high tide when the animal is underwater (Antoine & Quemerais-Pencreac'h, 1980; Ekaratne & Crisp, 1982). This pattern coupled with their specific feeding behavior allows the shell of *P. vulgata* to records local marine conditions in most of its distribution range: in the United Kingdom (Fenger et al, 2007), in France (Cudennec & Paulet 2021, 2022) or in Spain (Gutiérrez-Zugasti et al., 2017). Other patelloid species are also used as paleo-environmental trackers in the European Atlantic coast (García-Escárzaga et al., 2020), the Mediterranean (Prendergast & Schöne, 2017), South America (Colonese et al., 2012), or the Hawaiian Archipelago (Mau et al.,2021).

P. vulgata shell do not grow constantly through the year, growth being mainly driven by the local temperature conditions. In the southern part of its distribution (Spain), *P. vulgata* produces an annual growth line in summer, while in the North Sea they produce an annual growth line in winter. In the most temperate regions of its distribution, growth can be consistent enough to prevent the formation of annual growth line, despite annual variations in growth. The conditions of annual growth line formation show inter-individual heterogeneity, with summer growth lines for some specimens and winter growth lines for others in a single station in the Channel (Surge et al., 2013). Other studies did not find significative annual growth interruptions (Borges *et al*, 2016; Choquet, 1968; Thomson, 1980), strengthening the ability of this species to record environmental conditions accurately.

This animal's sclerochronology and isotopic signature are now relatively well-known, with several applicative studies having been conducted in Europe, mainly for paleo-climatic purposes (Surge & Barrett, 2012; Wang et al., 2012). Different attempts have been made to use this group of species as a marker of harvesting pressure (Harris et al., 2018) and seasonality, using stable isotopes (Shackleton, 1973; Bailey et al., 1983) or the distance from the last annual growth check (Bailey & Craighead, 2003) but there is no wide application of this approach to European shell middens yet. The objective of this study is thus to use stable oxygen isotopes from *Patella* sp. shells to improve our understanding of human occupations and dynamics on islands on the different period investigated here, from Late Neolithic to Early Bronze Age and Early Middle Age.

Table 1
Radiocarbon (^{14}C) dating of the different stratigraphic units and pit from PAP and BAL sites. See Pailler & Nicolas, 2019, 2022; Stéphan et al., in prep. for details. sc: square; ssc: sub-square.

Contexte	Sample Type	Lab. Code	Age BP	Age cal. (95.4 %)	reference
BAL SC07 − Late Neolithic/ Bell Beaker (c. 2900–2500 cal. BCE)					
US2202 (SC07)	charcoal	Lyon-11066	4275 ± 30	3003–2801 cal. BCE	Pailler & Nicolas, 2019
US2202 (SC07)	charcoal	Lyon-7742	3995 ± 30	2576–2467 cal. BCE	Pailler & Nicolas, 2019
BAL SC21 − Early Bronze Age 2 (c. 1900–1750 cal. BCE)					
US2500 (SC21)	charcoal	UBA-12761	3519 ± 24	1920–1761 cal. BCE	Pailler & Nicolas, 2019
PAP USX3 − Late Neolithic/ Bell Beaker (c. 2500–2200 cal. BCE)					
TR2, sc. B1, ssc. a, USX3a	Ox tooth	UBA-47602	3961 ± 29	2571–2348 cal. BCE	Stephan *et al.* in prep
TR2, sc. C1, ssc. c, USX3b	wood charcoal	Beta-656062	3880 ± 30	2465–2211 cal. BCE	Stephan *et al.* in prep
TR2, sc. B1, ssc. c, USX3b	sheep/ goat tooth	UBA-49606	3850 ± 34	2457–2204 cal. BCE	Stephan *et al.* in prep
TR0, USX3	wood charcoal	Beta-401666	3840 ± 30	2455–2201 cal. BCE	Pailler & Nicolas, 2022a
TR2, sc. A1, ssc. a, USX3c	wood charcoal	Beta-656063	3810 ± 30	2401–2141 cal. BCE	Stephan *et al.* in prep
PAP USX1 − Early Bronze Age 2 (c. 2100–1750 cal. BCE)					
TR0, USX1	sheep/ goat tooth	Beta-403488	3650 ± 30	2137–1936 cal. BCE	Pailler & Nicolas, 2022a
TR2, sc. B2, ssc. c, USX1	sheep tooth	Beta-656061	3640 ± 30	2135–1900 cal. BCE	Stephan *et al.* in prep
TR2, sc. C1, ssc. d, USX1	sheep tooth	Beta-656060	3620 ± 30	2123–1891 cal. BCE	Stephan *et al.* in prep
TR1, sc. D1, ssc. d, USX1	charcoal	UBA-47476	3512 ± 31	1926–1746 cal. BCE	Stephan *et al.* in prep
PAP USH3 − Early Middle Ages (c. 650–850 cal. CE)					
TR0, USH3	sheep/ goat tooth	Beta-401668	1270 ± 30	664–827 cal. CE	Pailler & Nicolas, 2022

2. Geographical context and study sites

Beg ar Loued (BAL) and Porz ar Puns (PAP) are two multi-layered settlement sites, respectively located in the middle (Molène Island) and in the south (Béniguet Island) of the Molène archipelago (Fig. 1, Tables 1 and 2).

Due to the relative sea-level (RSL) rise over the past thousands of years, the Molène plateau was progressively submerged, resulting in a substantial loss of intertidal areas (Fig. 2). From the beginning of the Late Neolithic (LN) to the end of the Early Bronze Age (EBA), the RSL rose from −4.3 m to −3.5 m (Stéphan et al., 2015; García-Artola et al., 2018), leading to a reduction in foreshore surface area from 40 km^2 to 31 km^2 (Pailler et al., 2014; Stéphan & Tissot, 2022). By the Early Middle Ages (EMA), the RSL had reached approximately −1.2 m, further constraining the intertidal zone to just 17 km^2. On Béniguet Island, three main sand-drift events were recently dated to around 2400 (LN), 1800 (EBA), and 600 cal. BCE (LBA-EIA) (Pailler et al., 2023). These episodes of sand invasion suggest episodic sand supplies to the coast and potential modifications of benthic habitats (rocky vs sandy) on the foreshore. These sandy events were associated with periods of enhanced storminess along the western coasts of France (Pouzet et al., 2018) and a strengthening of the sub-polar gyre in the NE Atlantic with NAO-

Table 2
Description of sampled trenches and pits. Detailed dates are given Table 1.

S.U. / pit	Site	Trench	Cultural period	# of analyzed shells	Comments
SC07	BAL	/	Late Neolithic/ Bell Beaker	22	pit (approx. 30-cm high) filled by brown silt nearby a dry-stone house, dense shell deposit rich in ecofacts
SC21	BAL	/	Early Bronze Age 2	22	pit (approx. 30-cm high) filled by a shell deposit with brown silt loam rich in archaeological materials nearby a dry-stone-house entrance
TR1_USX3	PAP	TR1	Late Neolithic/ Bell Beaker	5	shell layer, compact silt loam, not completely excavated
TR2_USX3	PAP	TR2	Late Neolithic/ Bell Beaker	10	shell layer, approx. 20-cm high, compact silt loam, highly rich in archaeological materials
TR0_USX3	PAP	TR0	Late Neolithic/ Bell Beaker	10	shell layer, approx. 20-cm high, compact silt loam, rich in archaeological materials
TR1_USX2	PAP	TR1	Early Bronze Age 1	10	mobile sand disrupted by rabbit holes, few limpets and few archaeological materials found around a dry-stone structure, nearly sterile in other trenches (exception of some limpet fragment in TR2)
TR1_USX1	PAP	TR1	Early Bronze Age 2	11	shell layer, approx. 10-cm high, slightly compact sand, rich in ecofacts including limpet shells with charcoals inside and few other kinds of archaeological materials
TR2_USX1	PAP	TR2	Early Bronze Age 2	10	shell layer, approx. 10-cm high, slightly compact sand, less rich in archaeological materials than TR1 and TR0
TR0_USX1	PAP	TR0	Early Bronze Age 2	10	shell layer, approx. 10-cm high, slightly compact sand, rich in archaeological materials
TR0_USH3	PAP	TR0	Early Middle Age	10	high layer of white and gray sands which includes a dense shell pit, few ecofacts and one human bone

conditions (Penaud et al., 2020; Valero et al., 2024, 2024). These climate changes primarily affect wind patterns and precipitation regimes, but the analysis of local pollen spectra does not reveal any drastic modifications in atmospheric temperatures during the mid and late Holocene in the area (Fernane et al., 2015; Lambert et al., 2019). Most of the vegetation changes observed between LN and EMA are limited to the gradual replacement of oak by alder, the decline in tree cover due to deforestation, and their replacement by ruderal plants and grasses (*Poaceae*) with the development of agriculture practices. Regarding sea surface temperature (SST), no significant variation is assumed during the mid- to late-Holocene period due to the specific hydrological dynamics affecting the Iroise Sea, with strong tidal currents that promote the mixing of deep and surface waters, resulting in a reduction of both seasonal and interannual variations, regardless of atmospheric temperatures (Le Boyer et al., 2009).

Excavated between 2003 and 2011, the BAL site has yielded a late Neolithic (LN) shell middens and two early Bronze Age (EBA) superimposed dry-stone houses dating from 2150 – 1750 cal. BCE, sealed by aeolian sand during the middle Bronze Age (Pailler & Nicolas, 2019). One pit (SC07) is filled with shells and dated to the LN and was found below the earlier house, while another one was found next to the entrance of the later house courtyard (SC21, Fig. 1E and Table 1). Considering the sea level variations, the settlement was about 100 m inland from the coastline (Pailler et al., 2014; Stéphan et al., 2019) during the occupation period. This insular community practiced agriculture and animal husbandry, supplemented by fishing on the foreshore, gathering shellfish and, to a lesser extent, hunting migratory birds. The material culture reveals that this group exploited local resources, namely clay, beach cobbles, and rock outcrops.

Excavated since 2021 through three trenches (TR0, TR1, TR2), the PAP site shows a series of occupation layers over several hundreds of square meters from the LN to the contemporary era, interbedded in the sand dune. The basal sequence (USX3) is composed of three silty layers (2570–2140 cal. BCE), the middle one (USX3b) being the richest in domestic wastes (ceramic, lithic industry, terrestrial and marine fauna), including many limpet shells. Pottery features some Conguel ware and some Bell Beaker sherds, uncovered in the top silty layer (USX3a). Then, a first sand dune layer (USX2), *c.* 0.4 m thick, deposited ~ 2350 cal. BCE (OSL dating; Stéphan *et al.*, *in prep*), is almost archaeologically sterile. Only a few square meters in TR1 yielded a rough stone structure, associated with few domestic wastes, suggesting a rather short occupation. Above it, a more substantial brown organic sand layer (USX1), 0.15–0.2 m thick, contains a rich shell midden dated to the EBA (2140–1740 cal. BCE). Within this layer, a dozen of small postholes might indicate some building. Over this latter layer, a lighter brown sand layer (USX0) yielded similar artefacts and ecofacts, probably related to the EBA, and remains of a dry-stone wall, possibly part of a house. On the top of USX0 and USX1, crisscrossing V-furrows suggest that these organic-rich layers, that fertilize the sand, have been cultivated, as it is regularly observed in contemporary settlements in Scottish archipelagos (Guttmann, 2005). These furrows, as well as rabbit holes, might have caused some material shifting but sherds refitting show limited displacement (<3m). The sequence continues with a thick (2 m) white sand layer (USH4) set up during the late Bronze Age/early Iron Age (1450–650 cal. BCE; Stéphan *et al.*, *in prep*). Above it, a series of pits, dated in EMA (USH3, 620–820 cal. CE, ^{14}C dating, Table 1) are filled with grey sand and domestic wastes (pottery, terrestrial and marine fauna) in various concentrations. At the same level, herringbone dry stone walls have been observed (Cailleux, 1950) and rabbit activity exhumed human bones, suggesting the presence of a possible cemetery.

3. Material and methods

3.1. Sampling strategies and limpet shell selection

For BAL, two pits infilling were analyzed in this study (SC07 and

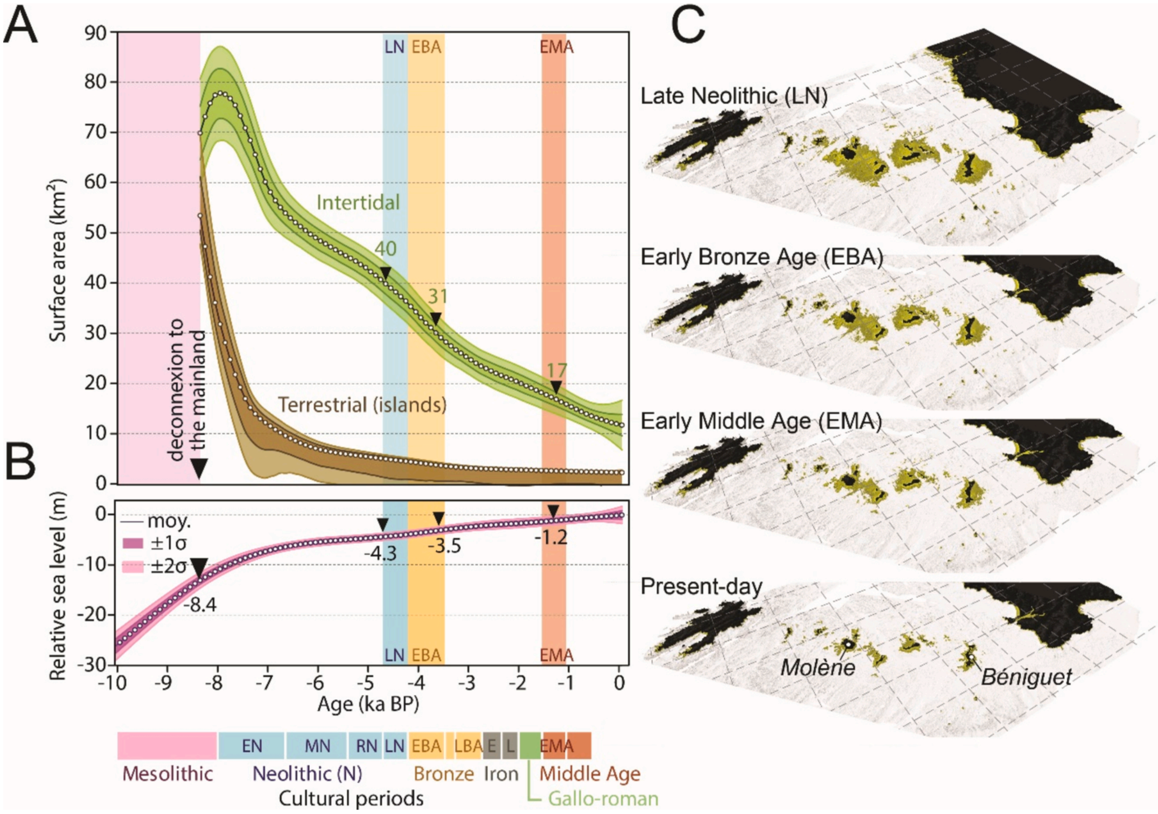

Fig. 2. Transformations of the Molène plateau coastal landscape over the last 10,000 years. A. Changes in intertidal and terrestrial (islands) surface areas (modified from Stéphan & Tissot, 2022). B. Relative sea-level curve for the western Brittany coast (modified from Garcia-Artolà *et al.*, 2018). C. Set of paleogeographic configurations of the Molène archipelago for various cultural periods, from the Early Neolithic to the present day. Supra-tidal, intertidal, and subtidal areas are represented in black, yellow, and white, respectively.

SC21), with 22 limpet shells selected for each (Table 2).

PAP has been studied through three trenches, from southwest to northeast (Fig. 1): TR1, TR2 and TR0. TR0 was studied through a cross-section and within three stratigraphic units: USX3, USX1 and USH3. TR1 and TR2 were excavated horizontally by stratigraphic units and by 5-cm cuts and were divided into grid (1 m^2 squares and 0.25 m^2 sub-squares). Ten well-preserved limpet shells from TR2_USX1, TR2_USX3, TR1_USX1, TR1_USX2 and five from TR1_USX3 were selected.

Considering the two sites, a total of 118 well-preserved shells were analyzed (Table 2).

Three limpet species can be potentially found nowadays in the Molène archipelago *Patella vulgata, P. depressa and P. ulysiponensis*. *P. vulgata* and *P. depressa* can be identified from flesh characters and with the radula structure, which are not available on archaeological specimens. However, these two species show similar isotopic signature (Fenger et al., 2007; García-Escárzaga et al., 2020). Shells were chosen

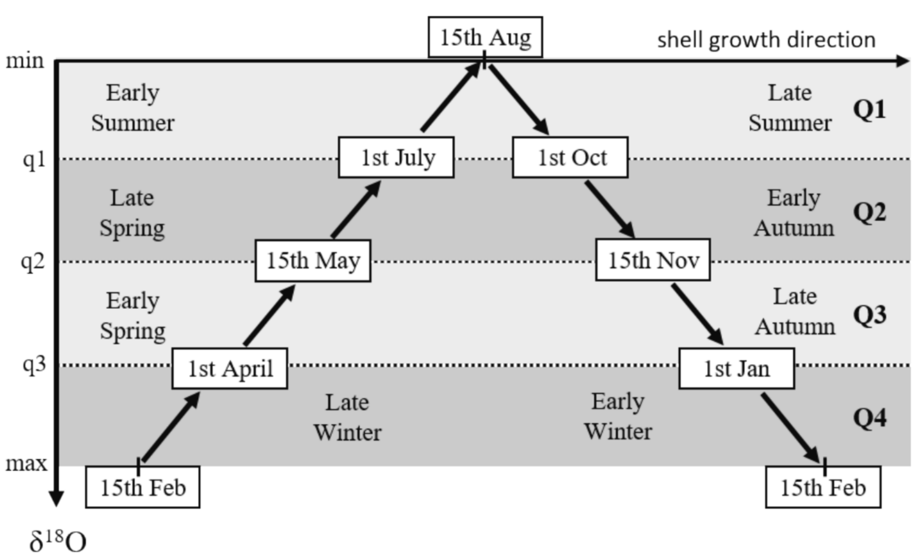

Fig. 3. Schematic representation of the annual temperature cycle recorded as a shell $\delta^{18}O$ profile. The harvesting season is determined by the marginal $\delta^{18}O$ values coupled with the last few samples trend.

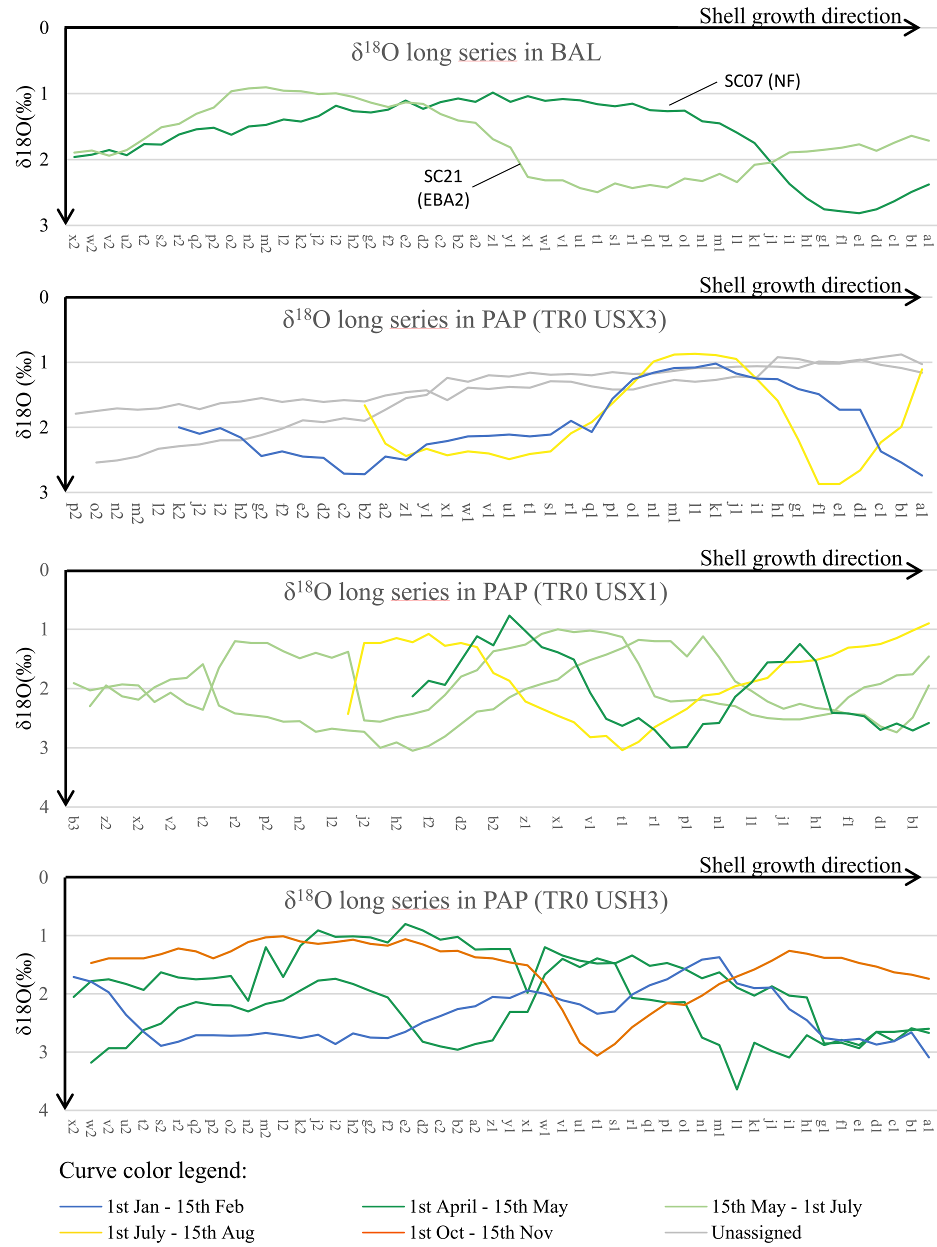

Fig. 4. Long series of δ^{18}O (‰) measured along limpet shell from the apex to the margin. Letters on abscissas represent sampling positions within the shell axis with "a1" (on the right of abscissa) being the sample the closest from the margin. Each plot represents one stratigraphy unit. Ordinate axes are reversed so temperature direction follows graphical δ^{18}O direction. Curve colors indicate season assignment: greens (spring), yellow and orange (summer), brown (autumn), blue (winter) and grey (no assignment).

for isotopic analyses according to their size (40 mm or as close as possible), their regularity, the shell integrity, the absence of epibionts on the inner side of the shell (indicating a dead-collected specimen), and the absence of recalcification along the margin.

3.2. Shell preparation and isotopic analysis

Shells were processed following the methods developed by Cudennec & Paulet (2022). Carbonate samples were drilled (with a 300 μm drill-bit) in the calcitic layers of the shells. Cross-sections were studied through long (29 to 73 carbonates samples) and short sampling series (10 to 14 sampling points) as described by Mannino *et al.* (2002) and on Annex. Only one (Molène) to four (Béniguet, TR0) long series were performed on each stratigraphic unit, the rest of the shells followed short sampling series. In both cases, the first sample was drilled as close as possible to the margin, corresponding to the last isotopic records of the animal's life, providing the seasonality data. The step between each hole was approximately 200 μm.

Long series aimed to characterize the δ^{18}O range reached by this species for each occupation period, and to determine the limits of each quartile of the seasonal range (see below). Shorts sequences allowed to determine the harvesting season for each shell. Carbonate samples were analyzed at the European Institute for Marine Studies (IUEM, University of Western Brittany, France), at the Pôle Spectrométrie Océan (PSO) on a KIEL IV carbonates device (Thermo Scientific) as described by Cudennec & Paulet (2022).

3.3. Season assignment

δ^{18}O in calcite shells is related to seawater salinity and reversely

Table 3
Proportion of limpets with no assigned harvesting season.

	BAL SC07	BAL SC21	PAP USX3	PAP USX2	PAP USX1	PAP USH3
number of analyzed limpets	22	22	25	10	31	10
number of unassigned limpets	3	5	2	0	2	0
proportion (%) of unassigned limpets	13.64	22.73	8	0	6.45	0

proportional to seawater temperature (Epstein et al., 1953; O'Neil et al., 1969). In Molène Archipelago waters, a site far from any significant river input, salinity was considered as stable so $\delta^{18}O$ was directly used as a temperature proxy. Harvesting seasons were determined according to the quartile method developed by Mannino et al. (2003, 2007). For each occupation period, all $\delta^{18}O$ data were distributed in quartiles (Fig. 3): the upper and lower ones (Q1, 0–25 % and Q3, 75–100 % of the annual range) correspond to annual extrema (winter and summer). The intermediate quartiles (Q2 and Q3, 25–75 %) correspond to spring and autumn and $\delta^{18}O$ trend at the shell margin (ascending or descending) was used to discriminate these two seasons. The marginal $\delta^{18}O$ value coupled with the trend of the previous samples allow a 1.5-month resolution, resulting in a half-season assignment (Fig. 3).

We defined season following the annual temperature cycle (Fig. 3, https://www.somlit.fr/brest/). Currently, thermal minimums in the Iroise Sea usually occur in February. Winter was then considered as running from the 1st of January to the 1st of April and summer from the 1st of July to the 1st of October (Fig. 3).

3.4. Statistics

Season proportion conformity to a homogeneous harvesting period (the null hypothesis) was tested within sites and stratigraphic units with $\chi 2$ test on R. Comparison of season repartition between sites and US were realized with Pearson's $\chi 2$ test with R software. Tests were realized at season level (4 periods).

4. Results

4.1. Season assignment accuracy

Long sampling series of $\delta^{18}O$ within the carbonate shell from the apex to the margin showed significant spatial variations (Fig. 4), but in most case, sinusoidal profiles can be depicted. Short series allowed a seasonal assignation for almost all the shells (Table 3, Annex). The impossibility to assign a harvesting season was usually caused by a flat $\delta^{18}O$ profile (Annex). All four seasons (with a three-month resolution) and all eight half-seasons (1.5-month resolution) were represented in our results, with a higher frequency in spring (Figs. 5 to 9).

4.2. Season assignment

4.2.1. Quartile bounds

While there was no significant difference of the average $\delta^{18}O$ values between stratigraphic units, extreme values (minima and maxima) and so quartile bounds were variable (Table 4). Most minimum and maximum values were close to 0.8 ‰ and between 2.8 and 3 ‰ respectively, except for three stratigraphic units points in Porz ar Puns: USX3 from TR2, USX1 from TR1 and USH3 from TR0. Within the EMA occupation of PAP, the maximum value of $\delta^{18}O$ reached 3.64 ‰, the highest value of the entire data set, corresponding to the lowest winter SST. This extremum affected the calculation of quartile bounds, but finally impacted the season assignment of only one limpet.

4.2.2. Limpet seasonality in Beg ar Loued: From Late Neolithic to Early Bronze Age

Within BAL, limpets from the two sampled pits showed similar

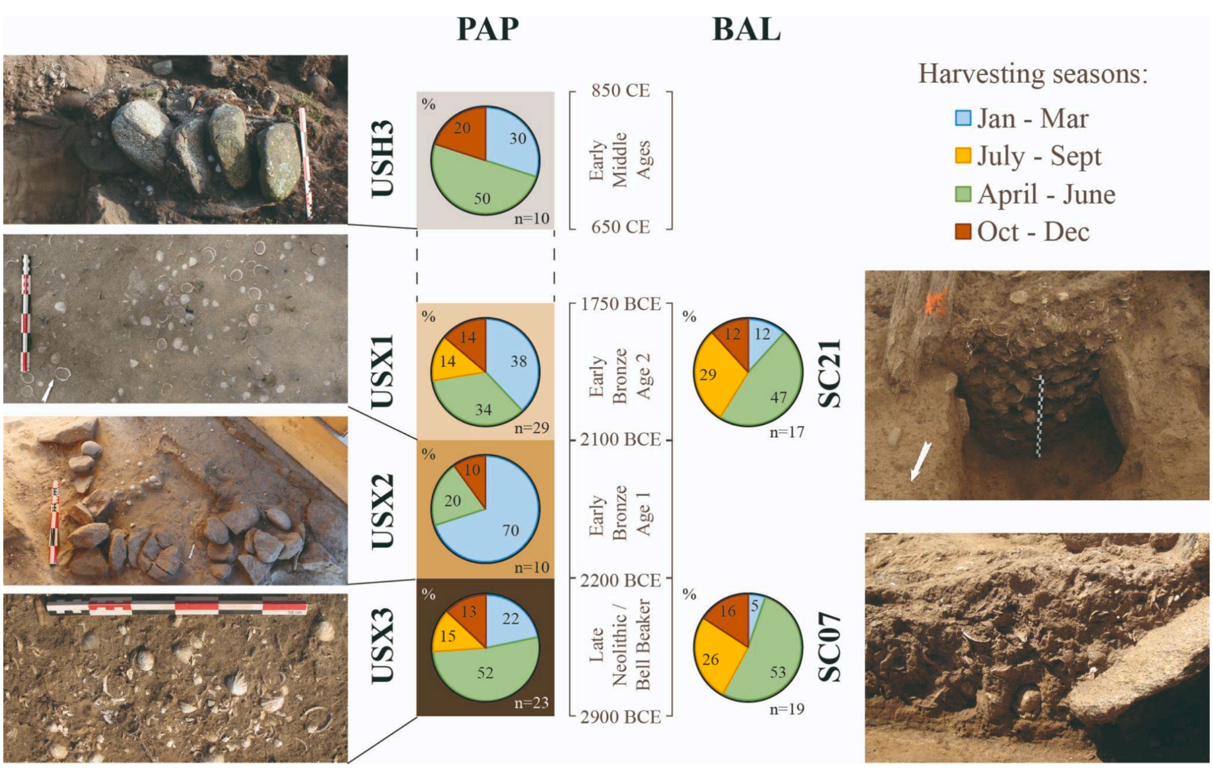

Fig. 5. Limpet harvesting season in Molène archipelago, from Late Neolithic to Early Middle Age. Pie charts represent the proportion of limpets assigned to each season, calculated on the three trenches.

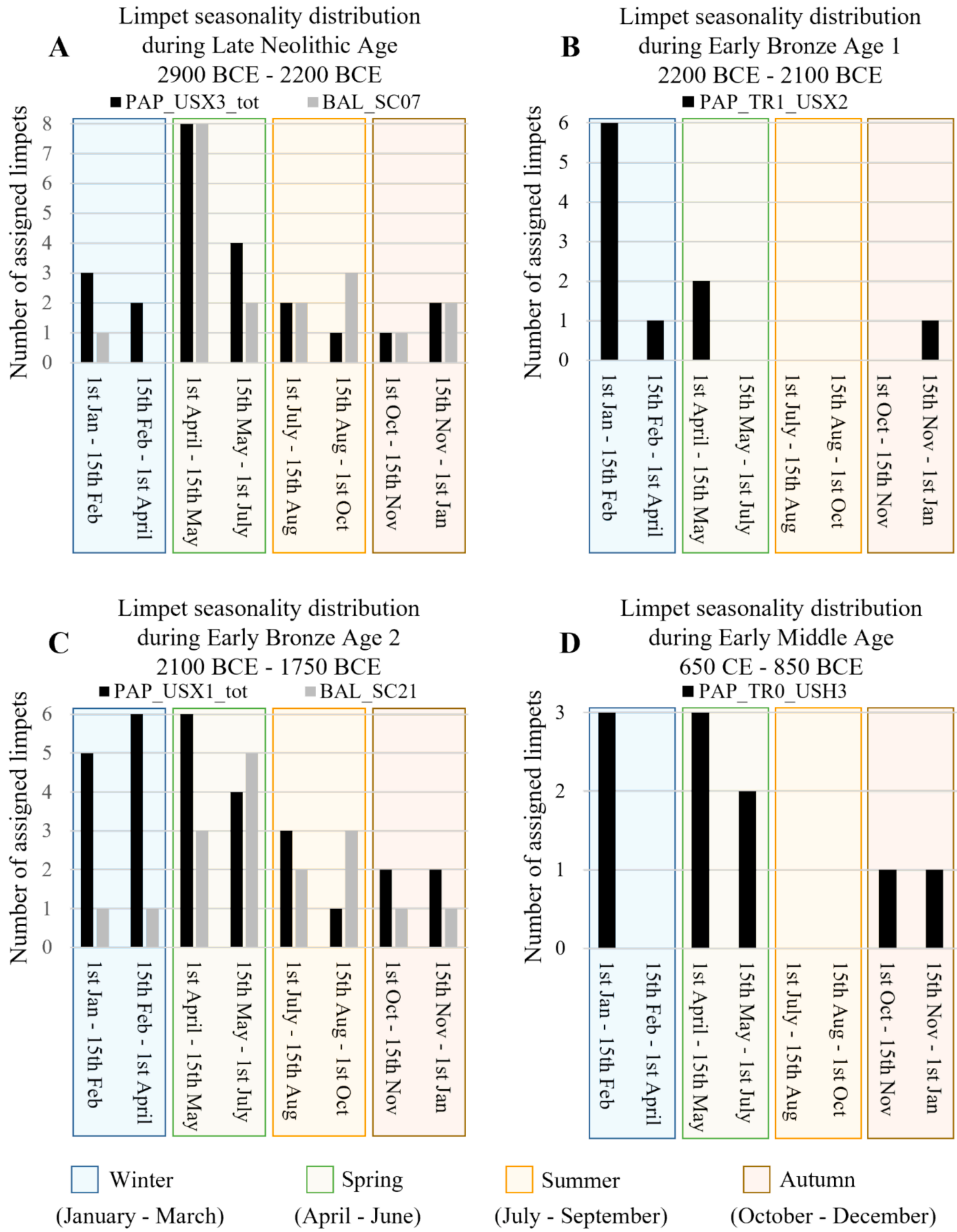

Fig. 6. Seasonality distribution of limpet from Molène Archipelago. PAP_USX3_tot and PAP_USX1_tot correspond to the proportions calculated from all the limpets of TR1, TR2 and TR0, within USX3 and USX1.

seasonal profiles (Fig. 5): dominance of limpets collected during spring and summer and few limpets from winter. However, the collection was significantly homogeneous during the year for the EBA but not for the LN (Annex). Within SC07, spring proportion reached 53 %, most of which were early spring (Fig. 6A). During the EBA, spring remained dominant (47 %), with a peak in late spring, but other seasons being more balanced (Figs. 5 and 6C, Annex).

4.2.3. *Limpet seasonality in Porz ar Puns: From Late Neolithic to Early Middle Age*

In Béniguet Island, stratigraphic units USX3 (2575–2141 cal. BCE, LN) and USX1 (2137–1746 cal. BCE, EBA) had been studied through three trenches, to reflect the spatial distribution of the middens. For USX3, when considering the three trenches, all the eight half-seasons of the year were represented (Figs. 5 and 6A), with a clear dominance of spring (Fig. 5, Annex). Within the USX2, limpet shells were present in TR1 only (except for a few fragments in TR2), with a lower density

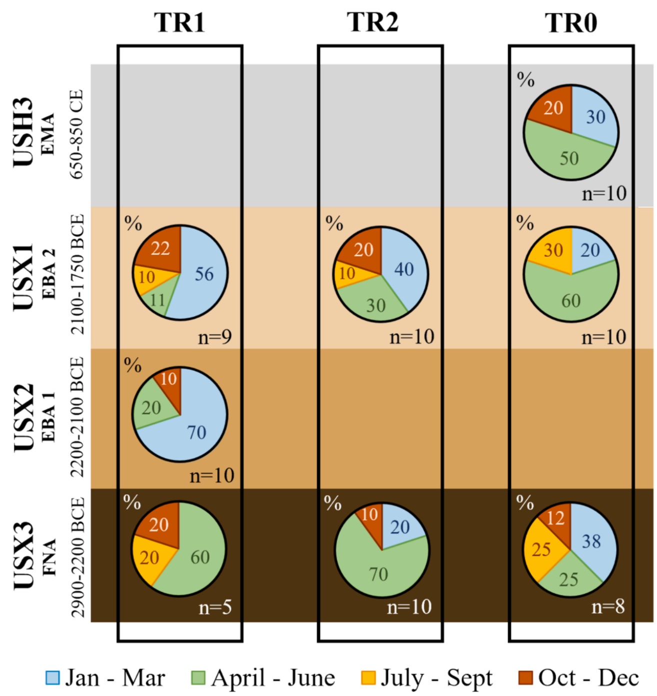

Fig. 7. Assignment of limpet harvesting season in Béniguet Island during periods from Late Neolithic Age to Early Middle Age. The pie charts represent the proportion (%) of limpets assigned to each harvesting period of the year.

compared to USX1 and USX3. All limpets were collected between the end of autumn and the beginning of spring, with 60 % of shells collected between January 1st and February 15th (Fig. 6B). Limpets from all seasons were retrieved within USX1 (Figs. 5 and 6C). Spring and winter were the two most abundant seasons, but harvesting homogeneity during the year could not be rejected (P-val = 0.117, Annex). Limpet shells were present within the USH3 in the three trenches (664–827 cal. CE., EMA) but only TR0 was analyzed. All harvesting seasons except summer are represented and half of analyzed shells were assigned to spring (Figs. 5 and 6D). Limpets from PAP were then mainly assigned to spring and winter, and this is consistent for all the considered periods, from LN to EBA.

4.3. Variations of seasonality within and among sites

4.3.1. Season assignment repartition within Molène archipelago

While in PAP winter and spring were the most represented periods, spring and summer dominated BAL for the LN and the EBA (Fig. 5). In both islands, spring was highly dominant during the LN (52 and 53 %) followed by summer in BAL (26 %) or winter in PAP (22 %). Despite these differences, season assignment through the year within BAL and PAP exhibited similar profiles at half-season level (Fig. 6A) even if this could not be confirmed by statistics at the season level (Annex). For the EBA stratigraphic unit, the seasonal distribution was even more significantly different between BAL and PAP (Annex). For BAL (SC21) spring remained highly dominant (47 %) and summer was the 2nd most represented season (29 %, Fig. 5). Within USX1 from PAP, spring shells were almost as abundant as winter shells (34 % and 38 % respectively). During the EBA, the most abundant period in BAL was late spring while this maximum was reached earlier in the year in PAP, in late winter and early spring (Fig. 6C). In summary, harvesting seasonality from Béniguet and Molène Islands do share more similarities during the late Neolithic Age compared to the early Bronze Age.

4.3.2. Season assignment and limpet location within Porz ar Puns site

For PAP, limpets from USX1 and USX3 were recovered from the three trenches (Figs. 7 and 8). For USX3 (LNA), spring was dominant in TR1 and even more in TR2 where 70 % of limpets were collected during spring and 20 % during the end of winter. In TR0, assigned harvesting seasons were more homogeneously represented with a slight dominance of winter (Figs. 7 and 8).

Inside USX1 (EBA), all seasons were represented within TR1 and TR2 (Fig. 7). Winter shells were highly dominant in TR1 (56 %) followed by autumn shells (22 %) while in TR0 all limpets were assigned to a period running from mid-February to mid-August, and spring shells were dominant (60 %). In TR2, limpets assigned to winter were abundant (40 %) followed by autumn shells (20 %). From TR1 to TR0, the proportion of winter shells decreased in favor of spring shells.

In TR1_USX1, most limpets came from the same sub-square (D1d). However, all seasons were represented within these 0.25 m^2 (Fig. 9). This is the only case were two opposite seasons are found in the same sub-square (summer with winter and spring with autumn). Within TR2_USX3, limpet collection is more structured with most of the spring shells deep in the trench (C1 and C2) and winter shells in front (A1a).

5. Discussion

5.1. Harvesting season determination robustness

Long series of $\delta^{18}O$ measurements along *Patella sp*. shell's growth axis permitted the acquisition of a sinusoidal signal corresponding to annual variation of temperatures and the determination of extreme values. In most cases, less than ten sampling points in the shell margin are sufficient to assign limpet to their harvesting season by obtaining the $\delta^{18}O$ trends and marginal value. Limpets having a highly variable growth rate (Cudennec & Paulet, 2021; Gutiérrez-Zugasti et al., 2017) the isotopic signal and then season assignment accuracy could potentially be affected, but this did not prevent the detection of limpets from all eight half seasons.

In some cases, however, $\delta^{18}O$ did not allow the seasonal assignment of collection. While unassigned limpets were not frequent, they represent more than 20 % within SC07, mainly corresponding to flat profiles, which remain unexplained.

5.2. Limpet harvesting seasonality in Molène archipelago through time

Patella sp. shells are highly abundant in archaeological coastal sites in Brittany (Dupont et al., 2009; Pailler et al., 2014; Mougne, 2019; Mougne & Dupont, 2023). As *Patella sp*. are ubiquitous in rocky shores, accessible all year-round and have a high meat yield compared to others marine mollusks, they represent an easily accessible protein source for insular populations (Dupont & Gruet, 2002; García-Escárzaga & Gutiérrez-Zugasti, 2021). In BAL and PAP, *Patella* sp. shells are associated to every human occupation from LN to EMA even within short-term occupation as in USX2 (Pailler et al., 2014; Pailler & Nicolas, 2019; Cudennec, 2019; Pailler et al., 2022; this study), highlighting the importance of this marine mollusk as food resource at least since LN as it was in Brittany coasts and other islands.

During the LN and the EBA, numerous evidences suggested permanent occupations of BAL and PAP sites: drystone houses in BAL; ard marks and partial wall in PAP (Pailler et al., 2014; Pailler & Nicolas, 2019; Pailler et al., 2022), as well as abundance of archaeological materials (marine mollusk shells, domestic animals and fish remains, charcoal, ceramics, lithic tools…). The presence of limpets collected during all seasons thus confirms the perenniality of these two human occupations on Molène and Béniguet Islands throughout the year.

During the LN, BAL and PAP sites presented similar seasonality profiles with all seasons represented in both islands and a higher proportion of limpets collected during spring. This preference is unlikely due to a higher availability of the resource. A more practical explanation

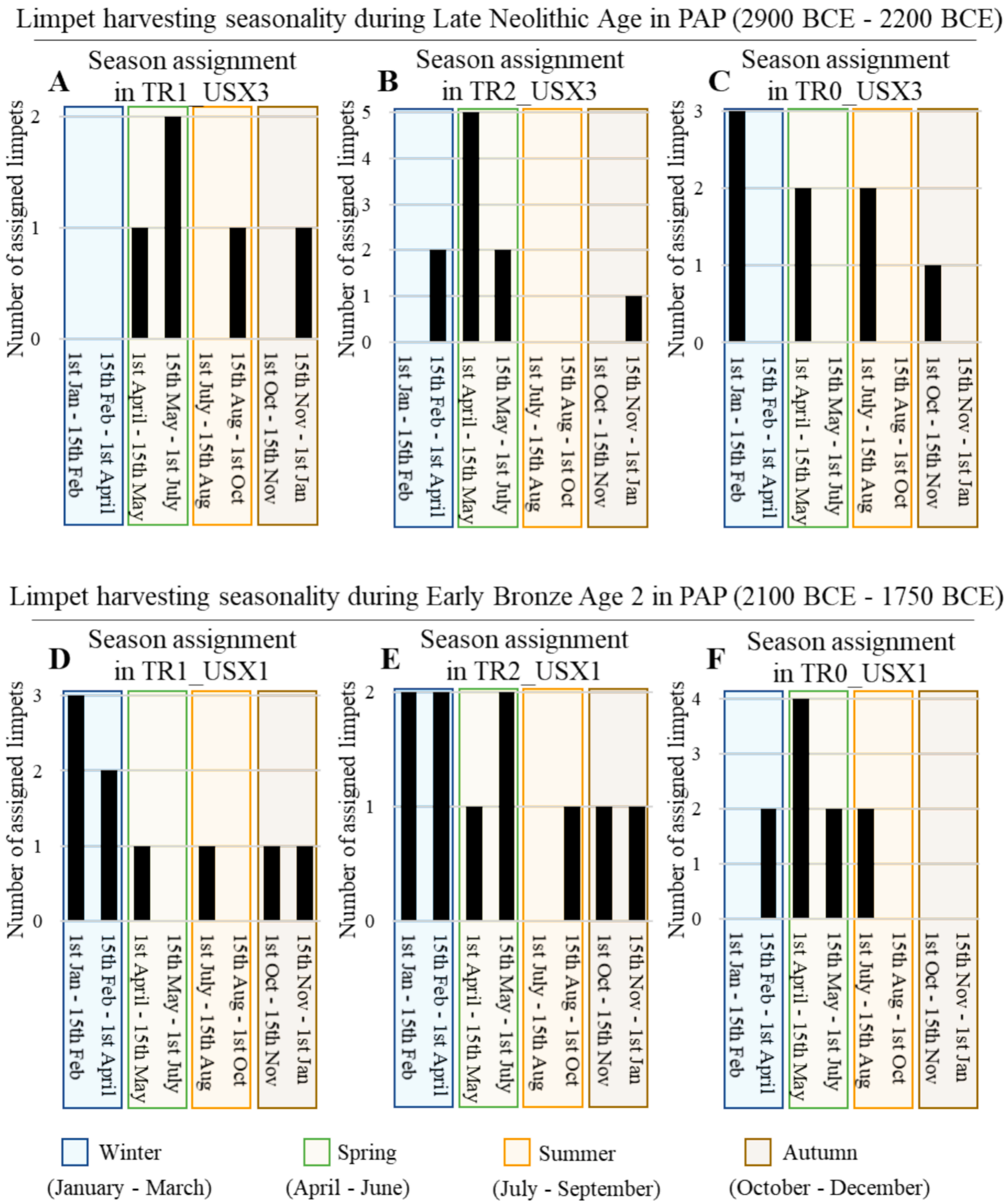

Fig. 8. Detailed seasonality distribution of limpet collected from Porz ar Puns (Béniguet Island) within the three trenches for Late Neolithic Age 2 (USX3) and Early Bronze Age (UX1).

could be the hungry gap: under temperate oceanic climate, fresh vegetable production is limited during winter (Diouf, 2021). Seasonal resources like cereals and fruits collected and stored during summer and autumn are consumed during winter, reaching a low level at the end of it. Limpet harvesting could then provide a supplementary resource in spring.

As for the LN, all seasons are represented during the EBA in both islands with a maximum harvesting proportion around spring. However, the two sites present shifted seasonality profiles with maxima of gathered limpets during the end spring for BAL and end of winter for PAP. This observation could similarly be explained by the hungry gap hypothesis (Diouf, 2021), and the slight shift between the two peaks of abundance could be linked with differences in other resources depletion on each island.

Within the aeolian sandy stratigraphic unit USX2, some *Patella* sp. shells were found within TR1 along with limited number of artefacts and in relation with a rough stone structure suggesting a temporary human occupation. All limpets were collected between the end of autumn and beginning of spring. This probably corresponds to a single occupation in relation to a winter activity (hunting, fishing during spring tide, seaweed harvesting, driftwood collection…) or result from an unexpected event (bad weather, shipwreck). It was, at the very least, a temporary activity at a time when the sand drifting of the island may have disrupted its long-term occupation (Stéphan *et al.*, *in prep*).

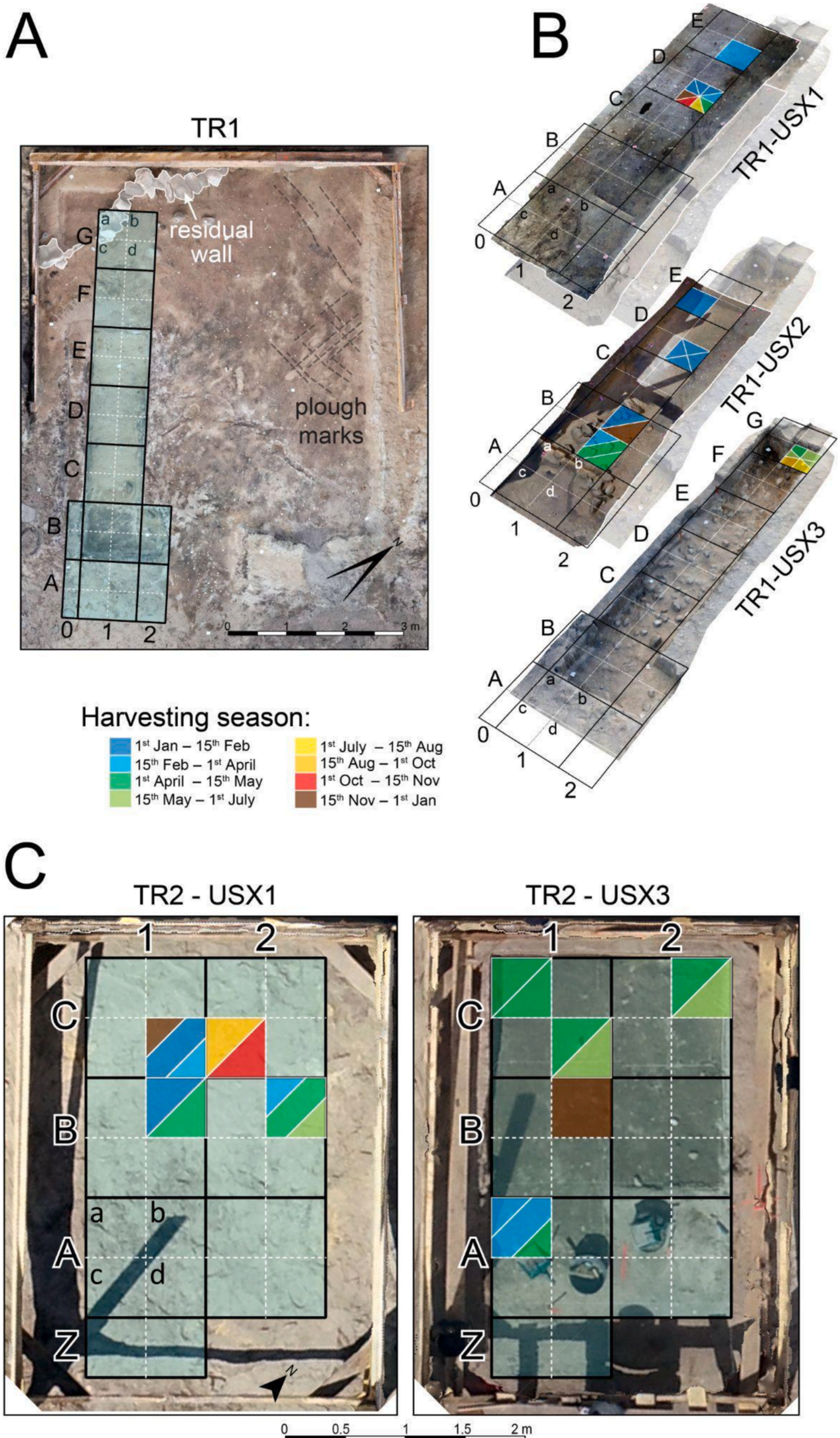

Fig. 9. Seasonality and location of shells within TR1 and TR2, Porz ar Puns site. Full squares represent 1 m^2 and dotted lines are the 0.25 m^2 sub-squares demarcation. Letters and numbers represent squares and sub-squares numbering and the colors represent the assigned season, as detailed in the figure.

Table 4
Range and quartiles determined from δ¹⁸O (‰) values within limpet shell margin of each stratigraphic unit of each sites and trenches. BAL: Beg ar Loued; PAP: Porz ar Puns.

	$\delta^{18}O$ min	$\delta^{18}O$ max	range	q1	q2	q3
BAL_SC07	0.984	3.118	2.134	1.517	2.051	1.560
BAL_SC21	0.797	2.978	2.181	1.342	1.887	2.433
PAP_TR1_USX3	0.832	2.865	2.034	1.340	1.849	2.357
PAP_TR2_USX3	0.627	2.798	2.171	1.170	1.713	2.255
PAP_TR0_USX3	0.870	2.980	2.110	1.398	1.925	2.453
PAP_TR1_USX2	0.852	2.945	2.093	1.375	1.899	2.422
PAP_TR1_USX1	1.249	2.965	1.715	1.678	2.107	2.536
PAP_TR2_USX1	0.865	2.802	1.937	1.349	1.833	2.317
PAP_TR0_USX1	0.770	3.170	2.400	1.370	1.970	2.570
PAP_TR0_MA	0.800	3.640	2.840	1.510	2.220	2.930

The USH3 from Porz ar Puns is the first tangible evidence of an occupation during the EBA in Molène Archipelago (Pailler & Nicolas, 2022): its archaeological content (domestic wastes, walls, and a possible cemetery) suggest a long-term occupation. The absence of limpet collected in summer could be explained diversely: a seasonal population movement, a focus on other seasonally available resources during this period or a bias in limpet sampling in this study.

5.3. Spatial distribution of seasonality in the middens: Impact of depositional and post-depositional processes

As SC07 and SC21 are pits and not stratigraphic units, the spatial approach is focused on Béniguet island only. In this work, we assume that the subsample of limpets for isotopic analyses we made well represents each occupation period. This means that the middens are considered as a spatially homogeneous structure. This is a debatable assumption, as we can see from our results, when limpets are spatialized (Fig. 9). By comparing the different trenches for USX1, we see a decreasing trend of winter shells and the disappearance of autumn shells toward the Northeast (from TR1 to TR0, Fig. 4). In trenches 1 and 2, we observe sub-squares (0.25 m^2) with three or even four seasons represented. In PAP where the deposit lies flat, results may be influenced by the number of deposition centers, (several shell deposition piles, thin homogeneous layers, or mixed model), and the rate of deposition. Fast accumulation of shells ends up with clusters of shells collected over short periods, while slow accumulation rates will produce mixed and more homogenous results (Hausmann & Meredith-Williams, 2017).

The primary conclusion drawn from this spatial approach is that the results are strongly influenced by the representativeness of the studied shells. Shell middens should be regarded as heterogeneous and patchy, especially if other archaeological features indicate that the site was occupied for several months every year. Therefore, it is essential to consider not only to increase the number of analyzed shells but also incorporating this spatial approach from the inception of the excavation.

5.4. Land management and dietary behavior

Limpet shells are highly dominant among the remains in both sites, but they were not the only food source. Indeed, even if limpets provide relatively high meat yield for mollusks, mollusks provide low meat yield compared to other taxa. Many other faunal remains were found as other marine invertebrates (mussels, crabs, sea urchin, *etc.*), fishes (gilt head bream, sea bass, *etc.*), cattle (sheep, ox, pig) and birds (Pailler & Nicolas, 2019; Pailler et al., 2022; 2023). Lipid analysis on pottery from BAL, demonstrated that ceramics were used to store or cook ruminant parts and dairy products, that were also part of the diet (Prévost et al., 2023). Besides, cereal caryopses (wheat, barley), beans and numerous grinding tools were detected in Molène Archipelago, depicting agro-pastoral activities during Late Neolithic Age (Dréano et al., 2007; Pailler et al., 2014). All these observations reinforced the likely role of limpets as buffer resource.

6. Conclusion

The aim of this research is to enhance our comprehension of the occupation patterns in the Molène Archipelago (Brittany, France) from the late Neolithic Age to the early Middle Age, through an analysis of the seasonality of limpet shell collection. The collecting season was determined by serial $\delta^{18}O$ measurements along the shell growth axis, achieving a 1.5-month resolution. Our results highlight similarities between the two permanent settlements, on Molène and Béniguet Islands, during the LN and the EBA. In these long-lasting settlements periods, limpets were collected all-year round, with variable intensity throughout the year (with a focus on spring during the LN, both on Molène and Béniguet) or between the islands (with a more balanced collection on Béniguet during the EBA, while Molène once again shows a focus on spring). This seasonal partitioning of limpet consumption can be related to the annual management of the different resources available for these insular populations. As shellfish are available all year round, they might have been used as a fallback resource after the depletion of other food sources during the winter months (this phenomenon being commonly known as the hungry gap). This work also shows that limpets, through their season of capture, reveal important information about the development dynamic of a shell midden. The collection date is a rare marker of the structure, dynamic and history of the midden and should also be considered this way for future studies.

CRediT authorship contribution statement

Jean-François Cudennec: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Cynthia Oliveira:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **Pierre Stephan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Funding acquisition. **Clément Nicolas:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Investigation, Conceptualization. **Yvan Pailler:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Fabien Dewilde:** Investigation, Formal analysis. **Éric Dabas:** Resources, Formal analysis. **Yves-Marie Paulet:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Annexes.

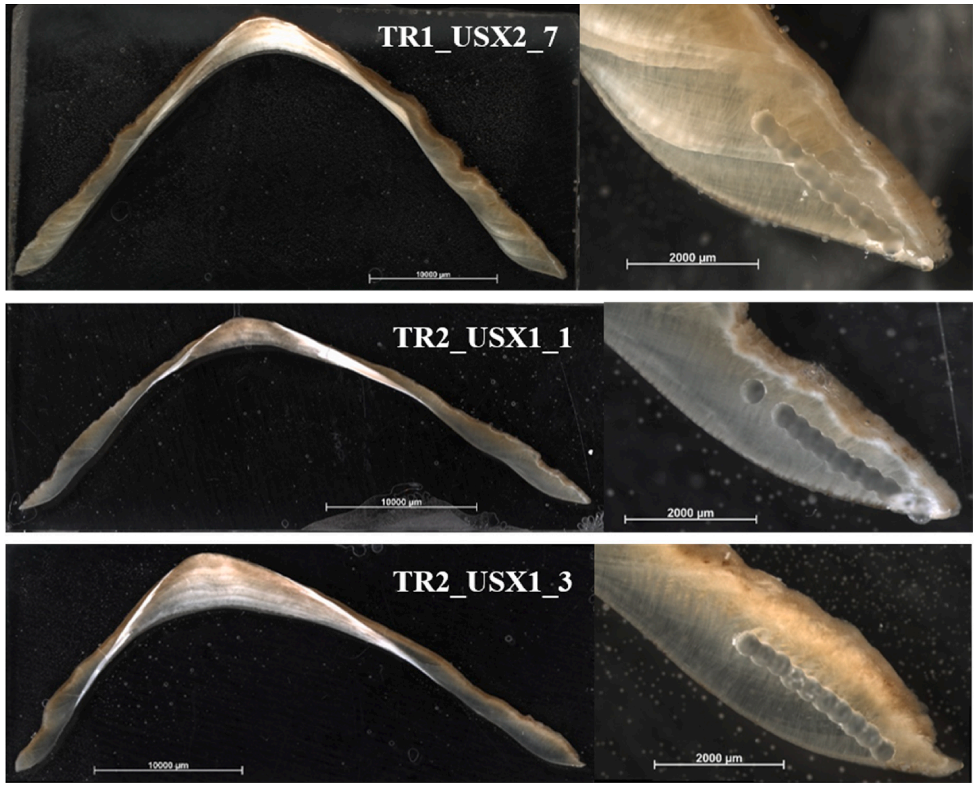

Fig. A. Limpet shell central sections and corresponding shell margin samplings for isotopic analyses.

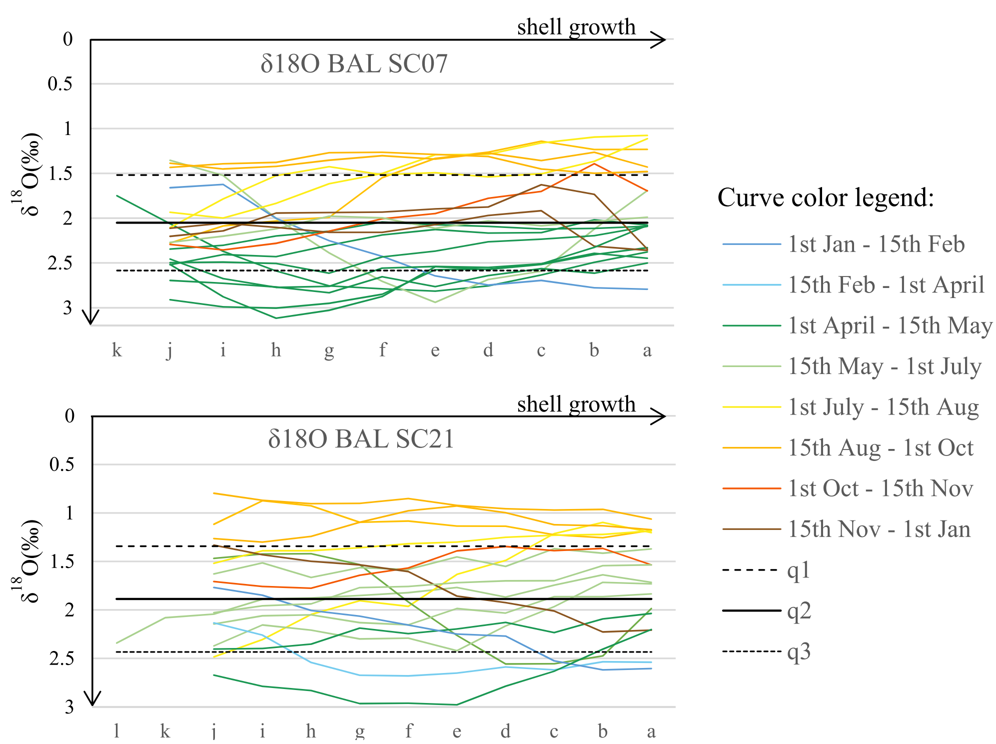

Fig. B. **$\delta^{18}O$ (‰) measured along limpet shell margins within Beg ar Loued site.** Letters from "l" to "a" on the abscissa represent sampling positions within the shell margin with "a" being the sampling point the closest from the margin. Oxygen isotopic results are gathered according to the limpet origin: SC07 and SC21 corresponding to stratigraphic units, Late Neolithic Age, Early Bronze Age respectively. Black lines and black dotted lines represent quartile bounds. Ordinate axes are reversed so temperature direction follows graphical $\delta^{18}O$ direction. Curve colors indicate season assignment: greens (spring), yellow and orange (summer), brown (autumn) and blue (winter).

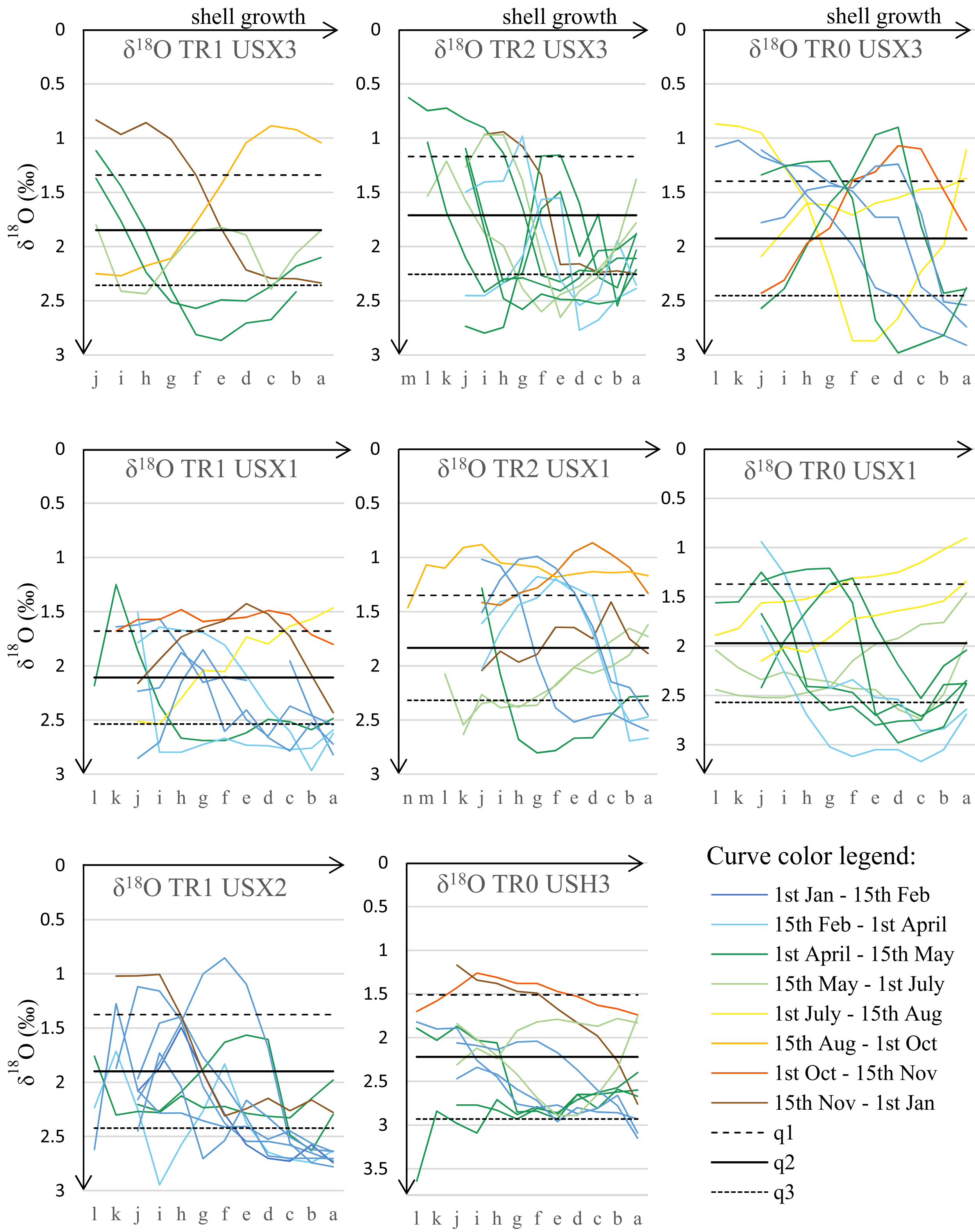

Fig. C. $\delta^{18}O$ (‰) measured along limpet shell margins within Porz ar Puns site. Letters from "n" to "a" on the abscissa represent sampling positions within the shell margin with "a" being the sampling point the closest from the margin. Oxygen isotopic results are gathered according to the limpet shell origins: TR1, TR2 and TR0 corresponding to trenches 1, 2 and 0 respectively; USX3, USX2, USX1 and USH3 corresponding to stratigraphic units (Late Neolithic Age, stratigraphic unit 2, Early Bronze Age and Late Middle Age respectively). Black lines and black dotted lines represent quartile bounds. Grey lines and grey dotted lines are examples of alternative quartile bounds. Ordinate axes are reversed so temperature direction follows graphical $\delta^{18}O$ direction. Curve colors indicate season assignment: greens (spring), yellow and orange (summer), brown (autumn) and blue (winter).

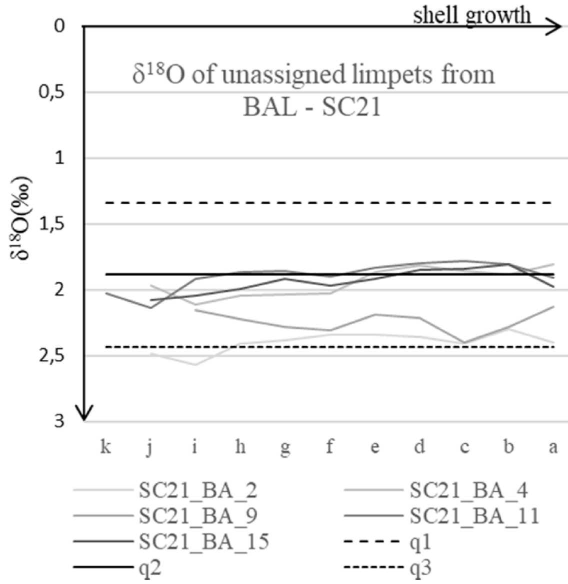

Fig. D. Examples of $\delta^{18}O$ (‰) profiles from limpet shells with no fished season assignation: $\delta^{18}O$ measured along limpet shell margins within the SC21 stratigraphic unit of Beg ar Loued site. Letters from "k" to "a" on the abscissa represent sampling positions within the shell margin with "a" being the sampling point the closest from the margin. Ordinate axes are reversed so temperature direction follows graphical $\delta^{18}O$ direction.

Table A
Test of season distribution homogeneity within Late Neolithic Age and Early Bronze Age stratigraphic units and pits from the two sites. χ^2 were calculated at season level (4 seasons, degree of freedom = 3). P.val (p-value) corresponds to the probability that each harvesting season proportion equals to 25 %. The minimal number of analyzed shells should be equal or superior to 20. *for less than 20 analyzed shells, χ^2 and the corresponding P.val might be slightly incorrect.

US_name.	khi_T.	P.val_T.	# of assigned shells.
BAL_SC07.	9.42*	**0.0242.**	19.
BAL_SC21.	5.82*	0.1205.	17.
PAP_USX3.	9.52.	**0.0231.**	23.
PAP_USX1.	5.90.	0.1168.	29.

Table B
Test of season distribution comparison between Late Neolithic Age and Early Bronze Age stratigraphic units and pits from the two sites. The upper part corresponds to χ^2 values, the down part to P-values. χ^2 were calculated at season level (4 seasons, degree of freedom = 3). P-value corresponds to the probability that the two compared harvesting season proportion are equivalent.

	BAL_SC07.	BAL_SC21.	PAP_USX3.	PAP_USX1.
BAL_SC07.		3.5521.	14.792.	32.532.
BAL_SC21.	0.3141.		9.6122.	21.53.
PAP_USX3.	**0.002003.**	0.02217.		8.0474.
PAP_USX1.	4.042×10^{-7}.	**8.168×10^{-5}.**	0.04505.	

Data availability

Data will be made available on request.

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