

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/108750/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Dias, Rita, Estrella-Martínez, Juan, Butler, Paul, Nederbragt, Alexandra, Hall, Ian, Barrulas, Pedro, Maurer, Anne France, Cardeira, Ana Mafalda, Mirão, José, Detry, Cleia and Bicho, Nuno 2018. Mesolithic human occupation and seasonality: sclerochronology, $\delta^{18}\text{O}$ isotope geochemistry, and diagenesis verification by Raman and LA-ICP-MS analysis of *Argyrosomus regius* (meagre) sagittae otoliths from layer 1 of Cabeço da Amoreira Mesolithic shell midden (Muge, Portugal). *Archaeological and Anthropological Sciences* 10.1007/s12520-017-0569-3

Publishers page: <http://dx.doi.org/10.1007/s12520-017-0569-3>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



Mesolithic human occupation and seasonality: sclerochronology, $\delta^{18}\text{O}$ isotope geochemistry, and diagenesis verification by Raman and LA-ICP-MS analysis of *Argyrosomus regius* (meagre) *sagittae* otoliths from layer 1 of Cabeço da Amoreira Mesolithic shell midden (Muge, Portugal)

AQ1

Rita AQ2 Dias, 1 

Email ritadupontdias@gmail.com

Juan Estrella-Martínez, 2

Paul Butler, 2

Alexandra Nederbragt, 3

Ian R. Hall, 3

Pedro Barrulas, 4

Anne France Maurer, 4

Ana Mafalda Cardeira, 4,5

José Mirão, 4

Cleia Detry, 6

Nuno Bicho, 1

¹ Interdisciplinary Center for Archaeology and Evolution of Human Behavior (ICArEHB) AQ3, Universidade do Algarve, Faro, Portugal

² School of Ocean Sciences, Bangor University, Bangor, Wales, UK

³ School of Earth and Ocean Sciences, Cardiff University, Cardiff, Wales, UK

⁴ Hercules Laboratory, Universidade de Évora, Évora, Portugal

⁵ Artistic Studies Research Center (CIEBA/FBAUL), Largo da Academia Nacional de Belas-Artes, 1249-058 Lisbon, Portugal

⁶ Faculdade de Letras da Universidade de Lisboa, Centro de Arqueologia da Universidade de Lisboa (UNIARQ), Lisbon, Portugal

Received: 7 May 2017 / Accepted: 15 November 2017

Abstract

We present preliminary sclerochronological analysis on 15 *Argyrosomus regius* (meagre) otoliths collected from two different human occupation levels from the Cabeço da Amoreira shell midden (Muge valley, Portugal). The otoliths were sectioned and observed under a reflected light stereomicroscope to examine seasonal growth rings. Carbonates collected from individual growth rings subsampled with a micromill sampling device were analyzed for their stable oxygen isotope content with the objective of determining the predominant season of capture and therefore season of site use, environmental conditions, and sites of resource procurement (local versus regional). The otoliths' stable isotope records show clear seasonality and a season of capture estimate that seems consistent with a “good season” (warmer season, i.e., from spring to late summer/beginning of autumn in this area) site use in the last occupation layer (the great majority of otoliths are from layer 1), except for four samples giving heavier oxygen isotope ($\delta^{18}\text{O}$) values that suggest colder conditions and only one with markedly positive $\delta^{18}\text{O}$ values. Potential effect of diagenesis on the otolith records was also assessed through coupled laser ablation–inductively coupled plasma mass spectrometry (LA-ICP-MS) and by micro-X-Ray diffraction (μ -XRD). Results revealed the presence of only aragonite and no traces of calcite, providing no evidence of diagenesis that could significantly alter isotope results and lead to erroneous interpretations. The implications of these results are discussed and compared with data from other archeological sites, as well as data from micromorphology regarding continuity or interruption of site use and other faunal remains.

Keywords

Otoliths

Seasonality

Mesolithic
Shell middens
Argyrosomus regius
Diagenesis

Introduction

The understanding of lifestyles of hunter-gatherer communities, especially the so-called complex hunter-gatherers, has become central to contemporary archaeological investigations. This has resulted from the clarification of what defines complexity and from the review of new and old models of the emergence of complexity (Arnold, 1996).

These models focus on phenomena like changes in settlement patterns, mobility and the broadening in subsistence, and advances in technology that all influence each other (together with other influences like ideology, which also have an influence the). Mesolithic populations are a good template for what are considered to be complex hunter-gatherers, with the so-called complex characteristics becoming clearer in the archaeological context (Neeley and Clark, 1990; Spikins, 2009).

Understanding human subsistence, settlement, and mobility during the Mesolithic is one of the key research topics in the context of human behavior changes and adaptation during the onset of the Holocene climatic shifts. The Muge shell middens, from the Portuguese Iberian Atlantic coast, have been pivotal in the investigation of these topics and have provided a very rich set of relevant data through several excavations that started in the mid-nineteenth century and continued through to the more recent excavations with new high-resolution methods.

From these archaeological contexts, zooarchaeological investigations, particularly in the Cabeço da Amoreira shell midden site, have provided a key information of both terrestrial and aquatic resources exploited by the Mesolithic populations and have also provided important insights into their settlement and mobility. However, beyond such traditional taxonomic analysis, sclerochronological studies are beginning to provide additional robust environmental data (e.g., seasonality) that are proving fundamental to address human settlement and mobility. Nonetheless, these sclerochronological investigations, especially from the late Pleistocene/Early Holocene archaeological context, are still in their early infancy and require additional systematic investigations to validate such approaches.

The archaeological record of the Iberian Atlantic Ocean coast at the beginning of the early Holocene Atlantic period (c. 8–5 ka BP) is marked by a shift in both human settlement and—although only partially—subsistence and technology in the Portuguese territory (Bicho, 2009, Bicho, 1994; Bicho and Haws, 2008). By then, human occupation had clearly shifted from coastal areas to river estuaries, such as the Tagus and Sado, and a change is observed in the nature of sites in the Tagus river, which consist of very large shell middens with long and complex stratigraphy marked by a matrix of shell remains and includes habitational structures and burials (Bicho et al., 2009). Nevertheless, changes seem to have been more profound with respect to settlement and technology than with respect to species composition, since the terrestrial species used at the sites are generically the same (red deer, wild boar, aurochs, rabbit) (Detry, 2007) and the same can be said for shellfish (peppery furrow shell, common cockle, and grooved carpet shell) (Lentacker, 1986a, b). The novelty comes with the much more broad and intense utilization of fish (Dias et al., 2016, Dias et al., 2015) and the abandonment of species not so easily accessible in these new territories like the common mussel and goats (Bicho, 2009; Detry, 2007).

AQ4

Mesolithic subsistence in the shell midden complex of Muge, although using a broad spectrum of terrestrial and aquatic resources, involved a particularly strong component of aquatic resources as proven by both human stable isotope and oligoelement (carbon and nitrogen) results (Umbelino, 2006) and faunal remains (Detry, 2007; Dias et al., 2015; An Lentacker, 1986a, b; Lentacker, 1994). This included not only shellfish but also an important contribution of fish, comprising a wide variety of *taxa* (*vide* Table 1).

Table 1

Fish species distribution by layer from the Cabeço da Amoreira 2008–2015 excavations

Order AQ6	Family	Taxa	1	2	3	4	Comb1
			18	8	2	1	1
Pleurotremata		Pleurotremata	1	0	0	0	1
	Carcharhinidae	Carcharhinidae	23	13	1	1	0
		<i>Carcharhinus plumbeus</i>	1	5	1	0	0
		<i>Carcharhinus</i> sp.	2	1	0	0	0

Order AQ6	Family	Taxa	1	2	3	4	Comb1
			18	8	2	1	1
		cf. <i>Carcharhinus plumbeus</i>	0	1	0	0	0
	Lamnidae		2	0	1	0	0
		<i>Carcharodon carcharias</i>	0	1	0	0	0
	Odontaspidae		0	1	0	0	0
	Sphyrnidae	<i>Sphyrna</i> cf. <i>lewini</i>	0	1	0	0	0
Hypotremata			48	78	13	11	1
	Myliobatidae	<i>Myliobatis aquila</i>	84	119	20	4	1
		Myliobatidae	9	12	3	1	0
Perciformes			1	0	0	0	0
	Salmonidae	Salmonidae	0	1	0	0	0
	Moronidae	<i>Dicentrarchus labrax</i>	41	139	17	33	1
		<i>Dicentrarchus</i> sp.	3	0	0	0	0
		cf. <i>Dicentrarchus labrax</i>	9	25	3	6	0
	Clupeidae	Clupeidae	2	11	1	2	0
		<i>Alosa</i> sp.	15	50	7	26	2
		cf. <i>Alosa</i>	2	10	1	4	0
		<i>Sardina pilchardus</i>	0	0	0	0	0
	Anguillidae	<i>Anguilla anguilla</i>	0	0	0	0	0
	Sciaenidae	<i>Argyrosomus regius</i>	55	89	5	8	1
		cf. <i>Argyrosomus regius</i>	9	19	0	0	0
	Mugilidae	cf. Mugilidae	16	61	7	13	0

Order AQ6	Family	Taxa	1	2	3	4	Comb1
			18	8	2	1	1
		<i>Mugil cephalus</i>	9	9	2	5	0
		Mugilidae	197	618	74	115	7
		<i>Chelon labrosus</i>	9	11	3	4	0
		cf. <i>Chelon labrosus</i>	0	1	0	3	0
		cf. <i>Liza</i>	11	90	2	10	0
		cf. <i>Liza aurata</i>	0	2	1	0	0
		cf. <i>Mugil cephalus</i>	4	1	0	4	0
		<i>Liza aurata</i>	15	7	3	1	0
		<i>Liza</i> cf. <i>ramada</i>	1	0	0	0	0
		<i>Liza ramada</i>	30	8	1	0	0
		<i>Liza</i> sp.	377	1315	172	193	1
	Cyprinidae	Cyprinidae	3	3	2	0	1
		cf. Cyprinidae	0	0	0	0	0
	Pleuronectidae	cf. Pleuronectidae	0	2	0	0	0
		<i>Platichthys flesus</i>	0	1	0	0	0
		Pleuronectidae	3	5	1	1	1
		<i>Hippoglossus hippoglossus</i>	2	0	0	0	0
	Soleidae	Soleidae	2	9	0	5	0
	Serranidae	Serranidae	1	39	6	10	0
		cf. Serranidae	1	11	3	7	0
	Sparidae	cf. Sparidae	2	9	2	0	0
		Sparidae	7	3	1	3	0
		<i>Sparus aurata</i>	14	47	9	3	0
		<i>Sparus</i> cf. <i>aurata</i>	0	4	1	1	0

Order AQ6	Family	Taxa	1	2	3	4	Comb1
			18	8	2	1	1
		cf. <i>Sparus aurata</i>	0	3	0	2	0
	Congridae	<i>Conger conger</i>	1	7	1	0	0
	Gadidae	Gadidae	1	0	0	0	0
			58	208	39	39	4
			1089	3058	405	516	22



AQ5

Otoliths are accretionary structures that are part of the orientation, motion, and auditory system of teleost fish—are important sources of information for archaeologists. Widely analyzed in modern fisheries investigations, they have been continuously growing in importance in archaeological and paleoenvironmental investigations, especially since the mid-twentieth century (Casteel, 1976; Disspain et al., 2011, 2015). Otoliths have been used as an accurate indicator of the age of fish since the late nineteenth century (Casteel, 2011, Casteel, 1976). The array of information they potentially record has been explored in the literature over the last decade and ranges from fish population structure and environmental reconstruction to very specific information about past occupation of a site, such as seasonality, subsistence, fishing strategies and methods, human adaptation to environmental change, and even trading routes (Andrus, 2011; Begg et al., 2005; Higham and Horn, 2000; Robson et al., 2012, 2015).

It has long been known that calcium carbonate (CaCO_3) is deposited on the surface of the otolith at seasonally variable rates, creating (in temperate regions) translucent and opaque zones representing fast (warm season) and slow growth (cold season) (Casteel, 1976), that could however be influenced by stress, gonad development, or starvation during spawning and therefore coupling otolith opacity and stable oxygen isotope composition can, and should, be used to estimate time of zone formation (Hoie and Folkvord, 2006). In fact, the regular deposition of increments makes them ideal for determination of fish age, growth, and diet (Radtke et al., 1996; Robson et al., 2012, 2015). Nevertheless, there have been few successful attempts to determine season of capture solely by the counting and interpretation of growth rings, especially the last increment (Higham and Horn, 2000; Van Neer et al., 1993). This lack of success has

several causes (a) growth rings that seem to be obvious in modern otoliths are not always as distinct in archaeological specimens because of a number of taphonomical issues, including the fact that the important area at the edge of the otolith is commonly damaged in these specimens; (b) the band counting technique is prone to error when carried out by an inexperienced researcher and the lack of archaeological reference material makes it difficult to obtain the necessary practice; (c) a large number of specimens are required; and (d) analysis becomes more difficult in longer lived animals since annuli tend to crowd towards the edge of the otolith. These difficulties are addressed by having multiple otolith readers (Beamish and McFarlane, 1983; Campana, 2001; Campana et al., 1995), the use of stable isotope geochemistry, and, to a lesser extent, the knowledge of ecology and biology of the species in question.

Otoliths are ideal structures for stable isotope analysis, being hard structures of somewhat long-lived organisms with marked growth rings (Hoie and Folkvord, 2006; Iacumin et al., 1992; Kalish, 1991; Radtke et al., 1996). Growth starts from before hatching to death through continuous deposition of CaCO_3 (Campana and Neilssra, 1985) that is metabolically inert and therefore independent of the subsequent physiological state of the fish since it cannot be remodeled or reabsorbed (Campana and Neilssra, 1985).

The measurement of oxygen isotope ratios ($\delta^{18}\text{O}$) in the CaCO_3 from the last growth increment of a shell or otolith has proven to be a successful approach for the assessment of temporal site occupation patterns in ancient communities (Monks, 1981; McKechnie and Moss, 2016; Shackleton, 1973; Wang et al., 2013). The use of this technique is based on the fact that the $\delta^{18}\text{O}$ of aquatic biogenic carbonate, in this case aragonite, is controlled by the $\delta^{18}\text{O}$ of the ambient water (a function of water temperature and salinity) from which the carbonate secretion occurs (Colonese et al., 2009; Iacumin et al., 1992; Radtke et al., 1996; Salgueiro et al., 2010; Thorrold et al., 1997; Wefer and Berger, 1991). CaCO_3 of otoliths accumulates in a continuous fashion over time. It is therefore possible to establish seasonal changes on oxygen isotopes and, although sometimes generically, the season of capture (Iacumin et al., 1992, p. 537).

AQ7

The use of carbon isotope ratio $\delta^{13}\text{C}$ in fossil otoliths, on the other hand, is more problematic due to its precipitation out of equilibrium with the total dissolved inorganic carbon species in sea water and variable “vital effect,” between different species and within the different individuals of the same species (Iacumin et al., 1992, p. 537). Some researches have pointed to the metabolic contribution of these values, since the long-term record of metabolic rates can produce important information on the evolutionary history of fish physiological

characteristics and their bioenergetic processes (Wurster and Patterson, 2003). $\delta^{13}\text{C}_{\text{max-min}}$ values have a significant negative covariation relation with $\delta^{18}\text{O}$ (CaCO_3) that suggest a more important change in metabolic rate through the fish's life in colder climates, characterized by shorter growth periods or a decrease of the summer-winter precipitation ratios. The magnitude of this variation is larger in the early ontogeny of the fish (Wurster and Patterson, 2003). In short, the isotopic composition of biomineral carbon varies according with average metabolic ratio and expresses the individual's metabolic response, consequence of the combination of physical and ecological setting. However, some researchers have advised against the use of this data for interpretation of metabolic rate when the composition of diet and dissolved inorganic carbon cannot be simultaneously determined (which is the case of this investigation) (Trueman et al., 2016). Therefore, these data was not used at this time.

The growing importance of stable isotopes methods comes from the emphasis given to economic assessments of prehistoric (and historic) populations and the necessity of having knowledge of temporal patterns of exploitation of certain resources in order to determine mobility and site use patterns associated with either seasonal or permanent (all year round) occupations. Likewise, the necessity for baseline isotopic data to reconstruct human diet has led to increasingly frequent isotope analysis (Richards and Hedges, 1999; van der Merwe et al., 2003). Significant developments in the area have come chiefly from fisheries research focused mainly on paleoenvironmental reconstructions and age determination for fish conservation and stock assessments (Assis, 2000; Griffiths and Hecht, 1995; Prista et al., 2009; Surge and Walker, 2005; Wang et al., 2011; Wurster and Patterson, 2001). Notwithstanding, some significant developments have been made in the application of the techniques in archaeological specimens for paleoenvironmental and seasonality investigations in shellfish (Colonese et al., 2012; Butler et al., 2009; Jones et al., 2008; Kennett and Voorhies, 1996; Mannino et al., 2003; Mannino et al., 2007; Quitmyer et al., 1997; Wang et al., 2013) and fish (Brewer, 1987; Davis et al., 2003; Higham and Horn, 2000; Robson et al., 2016; Wang et al., 2013; Wurster and Patterson, 2003) and ~~this "and" should be erased and a comma should be put in its place~~ size estimation in fish (Gabriel et al., 2012), and the importance of fish remains for reconstruction of environment and subsistence has now long been recognized (Hufthammer et al., 2010; McKechnie et al., 2014).

AQ8

Quantitative and qualitative data for fish in Mesolithic Portuguese sites is available, especially for the Sado's shell middens (Gabriel, 2015, Gabriel, 2011, 2007; Moreno García, 2010) and those in Muge (Dias et al., 2015; Lentacker, 1986a, b; Lentacker, 1994), as well as some assessments of subsistence

strategies, namely about size reconstructions of *Argyrosomus regius* specimens in Mesolithic and Epipaleolithic sites (Gabriel et al., 2012). However, data about temporal exploitation patterns in Muge is still scarce and mostly based on terrestrial faunal remains (Detry, 2008, Detry, 2007, 2000; Dias et al., 2015).

AQ9

AQ10

Here we examine seasonality of the last Mesolithic occupation of the Cabeço da Amoreira shell midden through the study of *A. regius* otoliths. This will provide a new insight to improve the reconstruction of human occupation patterns (season of capture) during the Mesolithic of the Iberian Atlantic Ocean coast.

We also ascertain the validity of isotopic data through testing diagenesis with Raman and laser ablation–inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis that have showed that no significant alterations occurred that could change isotopic values in a significant way, leading to erroneous interpretations.

Archaeological context

The Cabeço da Amoreira Shell midden is one of several shell middens in the Muge complex, known and excavated since the nineteenth Century. The middens are characterized by very large accumulations of shells in layers sometimes as large as 60/70 m in diameter and up to 4 m in height and containing more than 300 human skeletons (Athayde, 1940; Cunha and Umbelino, 1995; Umbelino, 2006). That being said, pieces of information about some of these middens are from the first excavations and a number of these have subsequently been destroyed or lost (Bicho et al., 2011, Bicho et al., 2010). Their characteristics initially lead to the assumption that these sites could be the consequence of extensive residential occupations prolonged in time, with possible seasonal rotations between them (Arnaud, 1993, Arnaud, 1987, Arnaud, 1986).

Additionally, Rolão (1999) argued that there were two types of midden: larger middens (like Cabeço da Amoreira) with residential characteristics and smaller middens with logistic functions.

AQ11

AQ12

AQ13

Cabeço da Amoreira is one of the largest shell middens with c. 60 m in diameter and c. 2.5 m to c. 3.5 m, located in one of the Tagus subsidiaries, the Muge River (Fig. 1). Starting with the 2008 project, a large (72 m²) excavation area was opened on the southwest quadrant (Fig. 2), along with profile cleaning of the old

excavations for a better vision of the stratigraphy and AMS dating (Table 2) that dated the beginning of occupations to c. 7.9 Ka BP (Bicho et al., 2011). Also, microstratigraphy studies revealed an intricate and laterally variable stratigraphic succession of layers and lenses that allowed new insights into site formation and anthropogenic activities at the site, suggesting periods of abandonment through nondepositional hiatuses and discrete geogenic sedimentation (Aldeias and Bicho 2016).

Fig. 1

Location of the Cabeço da Amoreira shell midden. Map with the Mesolithic shell middens in the Muge region. 1. Fonte da Moça I; 2. Fonte da Moça II; 3. Fonte do Padre Pedro; 4. Flor da Beira; 5. Cabeço da Arruda; 6. Moita do Sebastião; 7. Cabeço da Amoreira; 8. Cova da Onça; 9. Monte dos Ossos; 10. Magos de Cima; 11. Cabeço da Barragem; 12. Cabeço dos Morros; 13. Magos de Baixo adapted from André and Bicho (2016) and Bicho et al. (2013)

AQ14

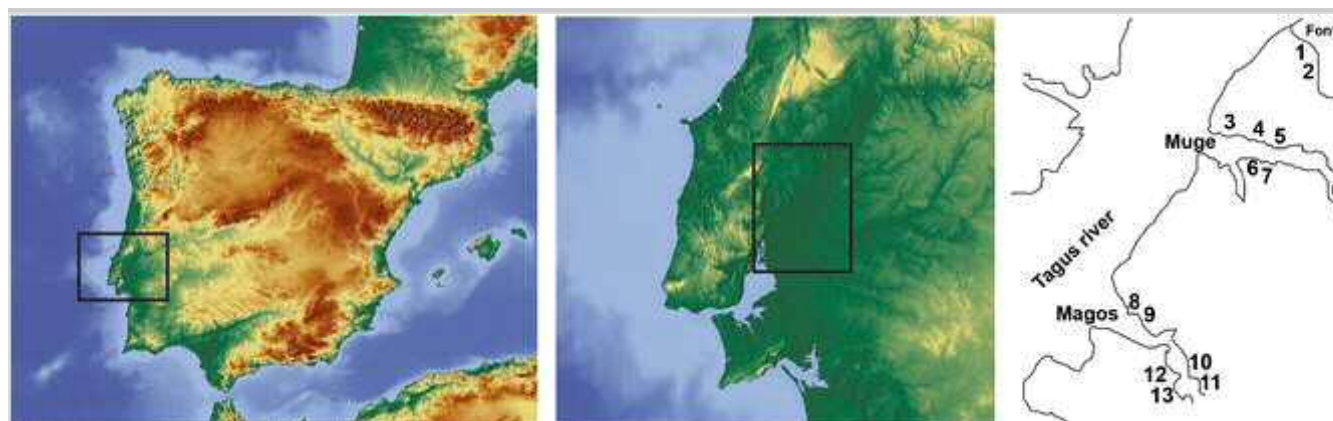


Fig. 2

Plan view of the excavation and testing in Cabeço da Amoreira adapted from Aldeias and Bicho (2016) and Bicho et al. (2013)

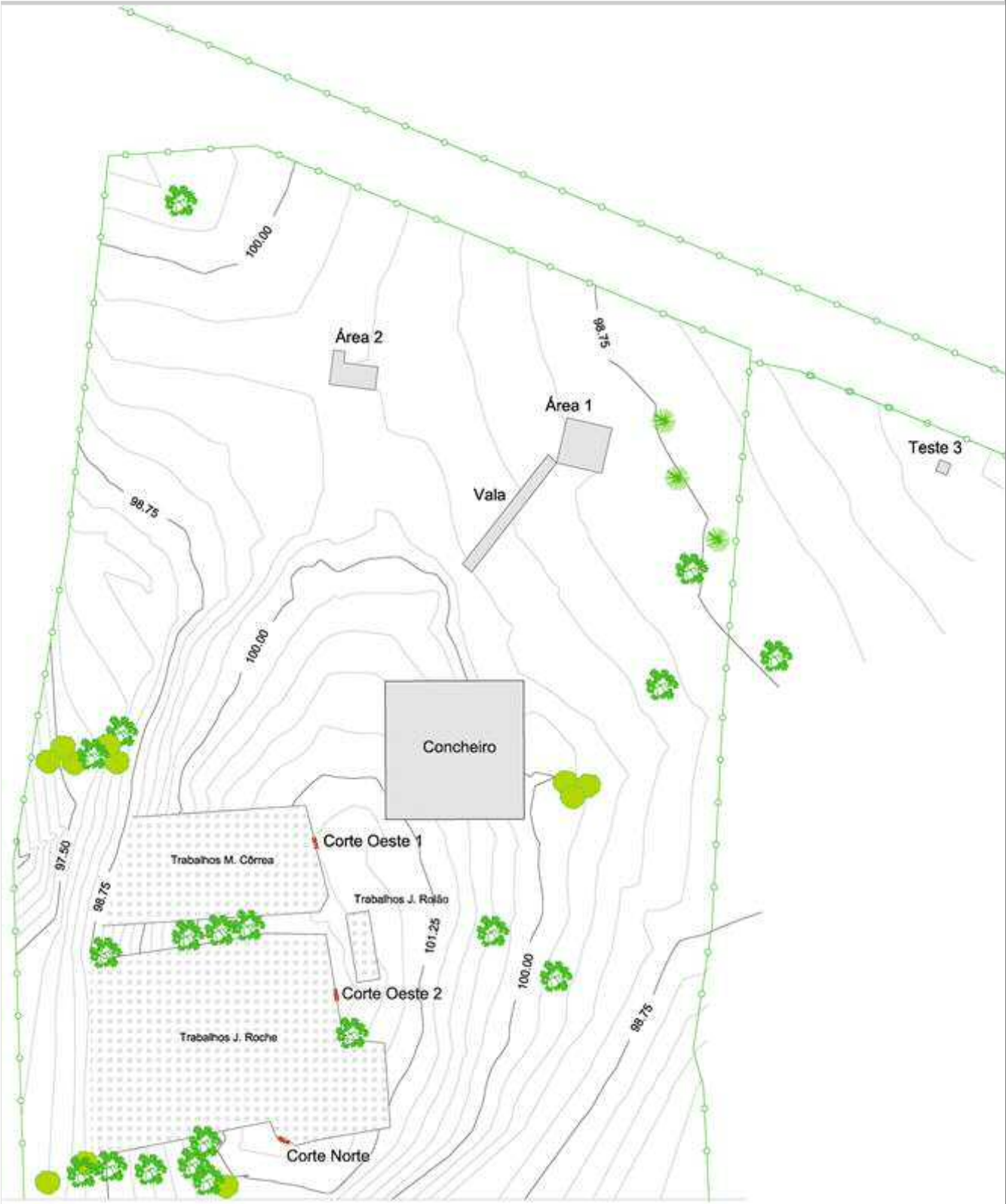


Table 2
AMS determinations from Cabeço da Amoreira according to Bicho et al., 2013
AQ15

Provenience	Context	Lab code	Material	Date BP	Cal BP 2σ	Posterior probability cal BP 2σ	F
-------------	---------	----------	----------	---------	-----------	---------------------------------	---

Provenience	Context	Lab code	Material	Date BP	Cal BP 2σ	Posterior probability cal BP 2σ	R
Multiple burial CAM-01-01	Cairn	WK-26796	<i>Homo sapiens</i> , bones	6329 ± 40	7145–6860	6329 ± 40	B (2)
Multiple burial CAM-01-01	Cairn	TO-10225	<i>Homo sapiens</i> , bones	6550 ± 70	7570–7325	6550 ± 70	R (2) A
Multiple burial CAM-01-01	Cairn	TO-10218	<i>Homo sapiens</i> , bones	6630 ± 60	7435–7185	6630 ± 60	R (2) A
Camada 3 (=camada 1b)	Cairn	Sac-2079	Shell	7050 ± 45	7545–7300	7050 ± 45	M al A
Camada 3 (=camada 1b)	Cairn	Sac-2080	Shell	7080 ± 80	7595–7275	7080 ± 80	M al A
Camada 1b	Cairn	WK-26798	<i>C. edule</i>	7145 ± 37	7590–7410	7145 ± 37	B (2)
Camada 3 (=camada 1b)	Cairn	Sac-2023	Shell	7260 ± 60	7740–7460	—*	M al A
Camada 1b	Cairn	WK-26797	<i>C. edule</i>	7291 ± 35	7510–7730	—*	B (2)
Burial 2011.2—layer 2b	Shell layers	Wk-32142	<i>Homo sapiens</i> , rib	6910 ± 40	7565–7430	7555–7455	B (2)
?	Shell layers	Beta-127450	<i>Homo sapiens</i> , bone	6850 ± 40	7565–7430	7575–7475	M et (2) A
Camada 22	Shell layers	Wk-30674	<i>Scrobicularia plana</i>	7356 ± 33	7800–7575	7685–7600	B (2)
Camada 22	Shell layers	Wk-30672	<i>Scrobicularia plana</i>	7360 ± 34	7805–7575	7685–7600	B (2)
Camada B	Shell layers	Wk-28050	<i>Scrobicularia plana</i>	7377 ± 33	7820–7590	7685–7600	B (2)
Camada C	Shell layers	Wk-28049	<i>Scrobicularia plana</i>	7193 ± 33	7900–7660	—*	B (2)

*Calibration with IntCal09 and Marine09 curves (Reimer, et al., 2009) using OxCal 4.1 (Ramsey, 1995). ΔR value used in the Homo samples of 140±40 from Martins et al., 2008

**Outlier results

Provenience	Context	Lab code	Material	Date BP	Cal BP 2 σ	Posterior probability cal BP 2 σ	R
Camada D	Shell layers	Wk-28048	<i>Scrobicularia plana</i>	7445 \pm 33	7630–7435 AQ22	—*	B (2)
Camada F	Shell layers	Wk-28047	<i>Scrobicularia plana</i>	7376 \pm 34	7820–7590	7685–7615	B (2)
Camada G	Shell layers	Wk-28046	<i>Scrobicularia plana</i>	7368 \pm 39	7815–7580	7685–7620	B (2)
Camada H	Shell layers	Wk-28045	<i>Scrobicularia plana</i>	7315 \pm 35	7765–7550	7690–7620	B (2)
Camada H	Shell layers	Wk-28044	<i>Scrobicularia plana</i>	7311 \pm 34	7760–7545	7690–7625	B (2)
Camada I	Shell layers	Wk-28043	<i>Scrobicularia plana</i>	7273 \pm 34	7710–7500	7695–7630	B (2)
Camada J	Shell layers	Wk-28042	<i>Scrobicularia plana</i>	7323 \pm 48	7795–7535	7695–7635	B (2)
Camada K	Shell layers	Wk-28041	<i>Scrobicularia plana</i>	7384 \pm 48	7845–7580	7700–7640	B (2)
Camada K	Shell layers	Wk-28040	<i>Scrobicularia plana</i>	7305 \pm 48	7770–7515	7705–7645	B (2)
Camada L	Shell layers	Wk-28039	<i>Scrobicularia plana</i>	7395 \pm 48	7855–7585	7710–7650	B (2)
Camada M	Shell layers	Wk-28038	<i>Scrobicularia plana</i>	7365 \pm 49	7825–7570	7715–7650	B (2)
Camada N	Shell layers	Wk-28037	<i>Scrobicularia plana</i>	7307 \pm 48	7775–7515	7720–7655	B (2)
Camada O	Shell layers	Wk-28036	<i>Scrobicularia plana</i>	7251 \pm 48	7706–7465	7725–7655	B (2)
Camada O	Shell layers	Wk-28035	<i>Scrobicularia plana</i>	7395 \pm 48	7855–7585	7730–7655	B (2)
Camada P	Shell layers	Wk-28034	<i>Scrobicularia plana</i>	7370 \pm 48	7830–7570	7745–7660	B (2)
Camada 2	Shell layers	Wk-30671	<i>Scrobicularia plana</i>	7417 \pm 34	7855–7615	7745–7660	B (2)
Camada 2	Shell layers	Wk-30673	<i>Scrobicularia plana</i>	7406 \pm 32	7855–7615	7745–7650	B (2)

*Calibration with IntCal09 and Marine09 curves (Reimer, et al., 2009) using OxCal 4.1 (Ramsey, 1995). ΔR value used in the Homo samples of 140 ± 40 from Martins et al., 2008

**Outlier results

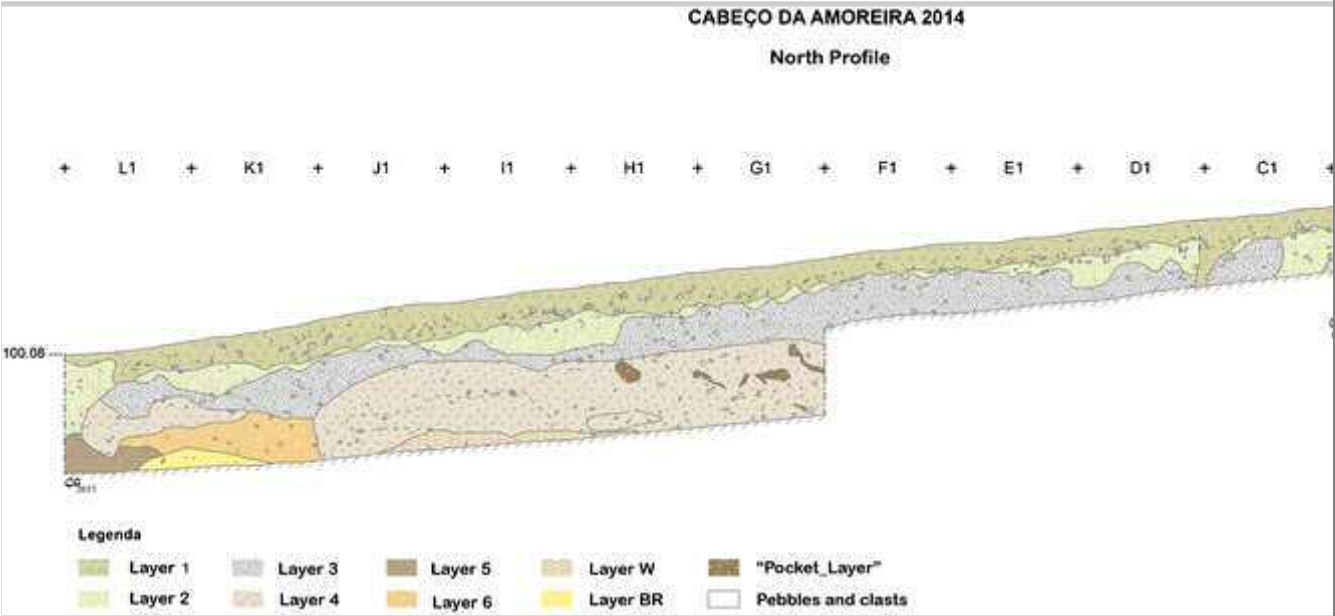
Provenience	Context	Lab code	Material	Date BP	Cal BP 2σ	Posterior probability cal BP 2σ	R
Camada Q	Bellow shell layers	Wk-28033	<i>Scrobicularia plana</i>	7479 ± 48	7930–7670	7810–7695	B (2)
Burial 2011.1	Bellow shell layers	Wk-32143	<i>Homo sapiens</i> , tibia	7132 ± 41	7785–7595	7775–7675	B (2)
Burial CAM-00-01	Bellow shell layers	TO-11819-R	<i>Homo sapiens</i> , bone	7300 ± 80	8015–7695	7840–7710	R (2) A
Hearth 1	Bellow shell layers	UGAMS-7196	Charcoal	6990 ± 30	7930–7735	7865–7725	B (2)
Pit. 1	Bellow shell layers	UGAMS-7197	<i>Scrobicularia plana</i>	7450 ± 30	7900–7665	7900–7735	B (2)
*Calibration with IntCal09 and Marine09 curves (Reimer, et al., 2009) using OxCal 4.1 (Ramsey, 1995). ΔR value used in the Homo samples of 140±40 from Martins et al., 2008							
**Outlier results							

Thus far, four main layers have been identified, with lateral sedimentary variations being attributed an alphabetic letter and sequential number for each 5-cm spit (Fig. 3). In addition, several test trenches were opened around the main excavation area, one of them 12-m long (Fig. 2) (Aldeias and Bicho, 2016; Bicho et al., 2010). The layers in the main area seem to have accumulated quite rapidly from c. 7900 to 7500 cal BP (Bicho et al., 2013). Also, other archaeological horizons with several layers were uncovered to the south of the main area, with no shell or faunal remains.

Fig. 3

Stratigraphic section of the north profile of the CAM excavation area in 2014 adapted from André and Bicho (2016) and Bicho et al. (2013)

AQ24



There are occasional pottery sherds in the mound surface, as well as Neolithic human burials, with one individual whose diet isotopic signal, mainly from terrestrial origin, contrasted with all other individuals in the older layers whose diet signal showed around 50% aquatic origin (Table 3) (Bicho et al., 2013; Umbelino, 2006). AMS dating for the skeletons is consistent with other Neolithic sites in the region which probably accounts for a Neolithic use of the site, after 7.4 Ka BP, sometimes intruding in the cairn layer.

Table 3
Percent of marine diet in human skeletons of Cabeço da Amoreira in Bicho et al. (2013)

Context	Lab code	Posterior probability (cal BP-2σ)	$\Delta^{13}\text{V}\text{C}$ (‰)	$\Delta^{15}\text{N}$ (‰)	% Marine diet
Burial 2011.2-Camada 2b	Wk-32142	7560–7455	– 15.78	12.82	58

Dates calibrated with OxCal 4.1 (Bronk Ramsey, 1995) based on the IntCal09 (Reimer et al. 2009). ΔR value of 140 ± 40 from Martins et al. (2008)
AQ25
AQ26
AQ27
AQ28

Context	Lab code	Posterior probability (cal BP-2σ)	Δ^{C} (‰)	Δ^{N} (‰)	% Marine diet
Burial 2011.1. base Jean Roche	Wk-32143	7780–7675	– 15.97	13.86	56
Multiple burial CAM-01-01	Wk-26796	7160–6910	– 16.9	12.3	46

Bellow shell midden	TO11819-R	7840–7710	– 16.3	–	50
Skeleton 7	Beta-127450	7575–7475	– 16.5	11.9	48
Multiple burial CAM-01-01	TO-10218	7425–7185	– 17.1	–	42
Multiple burial CAM-01-01	TO-10225	7475–7315	– 20.1 – 21.8	8.2 4.9	0 0
Skeleton 4	–	–	– 15.7	12.7	59
Skeleton 6	–	–	– 14.8	12.5	69
Skeleton 8	–	–	– 15.6	12	60
Dates calibrated with OxCal 4.1 (Bronk Ramsey, 1995) based on the IntCal09 (Reimer et al. 2009). ΔR value of 140 ± 40 from Martins et al. (2008) AQ25 AQ26 AQ27 AQ28					

The layer pertinent to this study is layer 1. It was excavated in an area of 12×12 m in 2008 to 12×9 in 2009 and 12×6 in 2010 and 2011 and mainly consists of abundant quartzite pebbles, some of them altered by fire, incipient soil formation (Aldeias and Bicho, 2016; Bicho et al., 2011, 2010), some shells, and 1089 fish remains (especially vertebrae) (Tables 1 and 4).

Table 4

Anatomical elements by species in layer 1

Taxa	Pectoral fin	Spine (neural/haemal)	Basioccipital	Cranium	Dentary
	0	0	0	0	0
<i>Pleurotremata</i>	0	0	0	0	0
<i>Carcharhinidae</i>	0	0	0	0	0
<i>Carcharhinus</i> sp.	0	0	0	0	0
cf. <i>Carcharhinus plumbeus</i>	0	0	0	0	0
<i>Hypotremata</i>	0	0	0	0	0
<i>Myliobatis aquila</i>	0	0	0	0	0
<i>Myliobatidae</i>	0	0	0	0	0

Taxa	Pectoral fin	Spine (neural/haemal)	Basioccipital	Cranium	Dentary
Perciformes	0	0	0	0	0
<i>Dicentrarchus labrax</i>	0	0	1	0	0
<i>Dicentrarchus</i> sp.	0	0	0	0	0
cf. <i>Dicentrarchus labrax</i>	0	0	0	0	0
Clupeidae	0	0	0	0	0
<i>Alosa</i> sp.	0	0	0	0	0
cf. <i>Alosa</i>	0	0	0	0	0
<i>Argyrosomus regius</i>	0	0	1	0	0
cf. <i>Argyrosomus regius</i>	0	0	0	0	0
cf. Mugilidae	0	0	0	0	0
<i>Mugil cephalus</i>	0	0	0	0	0
Mugilidae	0	0	9	0	0
<i>Chelon labrosus</i>	0	0	0	0	0
cf. <i>Liza</i>	0	0	0	0	0
cf. <i>Mugil cephalus</i>	0	0	0	0	0
<i>Liza aurata</i>	0	0	0	0	0
<i>Liza</i> cf. <i>ramada</i>	0	0	0	0	0
<i>Liza ramada</i>	0	0	2	0	0
<i>Liza</i> sp.	0	0	0	0	0
Cyprinidae	0	0	0	0	0
Pleuronectidae	0	0	0	0	0
<i>Hippoglossus hippoglossus</i>	0	0	0	0	0
Soleidae	0	0	0	0	0
Serranidae	0	0	0	0	0

Taxa	Pectoral fin	Spine (neural/haemal)	Basioccipital	Cranium	Dentary
cf. Serranidae	0	0	0	0	0
cf. Sparidae	0	0	0	0	0
Sparidae	0	0	0	0	1
<i>Sparus aurata</i>	0	0	0	0	0
<i>Conger conger</i>	0	0	0	0	0
Gadidae	0	0	0	0	0
Unknown	1	2	1	1	0
	1	2	14	1	1



The quantity of these so-called thermoclasts ($N = > 80,000$) and its dispersion, all over the midden, the fact that there was no obvious mixing or intrusions, dip, and strike of artifacts was random, and the impossibility of them being naturally deposited lead to the conclusion that this could be a cairn, intentionally made to protect the shell midden (Bicho et al., 2010, 2013, in press; Bicho and Gonçalves, 2016.).

Environmental/climatic and hydrological setting

Until fairly recently, the Holocene epoch was believed to be a climatically stable period (McManus et al., 1999). However, recent high-resolution paleoenvironmental studies (e.g., high-resolution sediment paleoproxies, ice cores, dust records) have revealed a substantial climate at a range of timescales relevant to societal development within the last 11 ka BP (Rodrigues et al., 2009).

The development of Mesolithic technology and settlement systems on the Iberian Atlantic Ocean coast has been linked with climate variability within the Holocene, including (1) the appearance of a great estuarine lake in the Tagus valley during the Atlantic period as a consequence of increasing sea level, (2) subsequent geomorphological and coastal environment alterations, (3) the decrease in upwelling along the Atlantic Portuguese coast (Haws, 2003; Monge Soares, 2006, Monge Soares, 2005), (4) warm sea surface temperature levels for the Iberian Atlantic coast (Rodrigues et al., 2009), and finally (5) the 8.2-ka BP cold event (Bicho, 2009; Bicho et al., 2010).

Information on the paleoenvironmental conditions of the Atlantic Portuguese coast has been acquired through a series of terrestrial cores (Cearreta et al., 2003; da Conceição Freitas et al., 2003; Fletcher, 2005; Fletcher et al., 2010; Santos and Fernanda Sánchez Goñi, 2003; Schriek, van der Schriek, 2004; Schriek et al., Van Der Schriek et al., 2007; van der Knaap and van Leeuwen, 1997) and deep-sea cores (Bard et al., 1987; Fletcher et al., 2010; Park, 1998; Penaud et al., 2010; Roucoux et al., 2001; Schönfeld and Zahn, 2000; Turon, 2003; VOELKER et al., 2006; Zahn et al., 1997), macro- and microbotanical remains (Araújo and Almeida, 2013; Figueiral, 1993; Figueiral and Carcaillet, 2005; Figueiral and Terral, 2002; Haws, 2003; Monteiro, 2012; Van Leeuwaarden and Queiróz, 2003; Zambujo and Lourenço, 2002; Zilhão et al., 1996), and both macro- and microfaunal remains (Bicho, 2003; Bicho et al., 2011; Cardoso and Rolão, 1999; Dias et al., 2016; Haws and Valente, 2006; A. Lentacker, 1986a, b; An Lentacker, 1986a, b; Moreno-García, 2011; Póvoas, 2001),

Lentacker (1986a, b) concluded that the microfaunal assemblage of the Muge's shell middens was similar to species found in Pleistocene contexts with the presence of *Arvicola sapidus*, *Pytimis duodecimcostatus*, *Microtus agrestis*, *Apodemus sylvaticus*, and *Eliomys quercinus*. Data from the microfaunal assemblage of coeval sites in the Iberian Peninsula are consistent with this panorama (Araújo and Almeida, 2013, Andrus, 2011, Gabriel 2010, Moreno García, 2010, Póvoas, 2001).

AQ29

AQ30

Vegetation evolution seems to suggest a transition from a continental/dry climate to an oceanic/moist climate indicated by a mitigation of seasonal contrast (Fletcher et al., 2010). The Atlantic woods continued their evolution during the Boreal (9–8 ka BP), following the temperature and humidity rise and climatic stability characteristic of the Atlantic period. Nevertheless, there is always a higher presence of mixed complex forests in coastal areas like Guadiana and Sado (Costa Tenorio et al., 2005). Microfaunal data show that the identified species are consistent with temperate forest or Supra/Meso-Mediterranean forested environments.

AQ31

AQ32

During the Holocene, the Tagus hydrological regime was influenced by lithology regional tectonic climate (Julião et al., 1998). At present, the Tagus hydrographic basin ($\sim 80,629 \text{ Km}^2$) has a great variety of physiographic aspects, ranging from mountainous regions to low marginal areas, like the estuary (Costa,

1999). Floods are a common phenomenon in the Tagus basin partially because its geomorphological characteristics lead to surface runoff from rainwater resulting in water erosion processes that increase flood potential with variations in outflow throughout the year (Julião et al., 1998; Ramos and Reis, 2001) and also because of the climatic characteristics of the basin, with higher precipitation on the north edge (higher altitude). Precipitation is very irregular inter-annually and even monthly.

The interaction between the fluvial system and the ocean is influenced by both climatic variability and sea level variations (dos Santos, 2010).

Geological investigations (e.g., van der Schriek, 2004; van der Schriek et al., 2007; van der Schriek et al., 2008) and Soares on the ocean reservoir effect (Soares, 2005) in the Muge valley and by Rodrigues et al. (2009) and Santos in her PhD dissertation (dos Santos, 2010) have provided important information about the influence of brackish water and chemical salt water in the estuary. Rodrigues et al. (2009) and dos Santos (2010) evaluate this influence by presence of marine diatoms or marine affinity diatoms and C_{37} alkenones. Works of van der Schriek and Soares, on the other hand, established the beginning of the brackish water fill of the Muge valley between 8.3 and 8.0 ka BP (Bicho et al., 2010; van der Schriek et al., 2008) essentially coinciding with the shell middens' first occupation (Bicho, 2009).

AQ33

The decrease of the upwelling along the Portuguese coast certainly affected marine productivity in the Estremadura coast at the onset of the Holocene (Bicho, 2009; Bicho et al., 2010; Bicho and Haws, 2008). Although a seasonal phenomenon today, it was not a constant in both the late Pleistocene and the beginning of the Holocene, with a decrease in the *upwelling* starting at ~ 20.0 ka BP (when it was at its maximum) but still three to seven times greater than present day (Rodrigues et al., 2009; Salgueiro et al., 2010; dos Santos, 2010). The Pre-Boreal and the Boreal periods saw further decreases, corresponding to the bond 6 (9.4 ka BP) and bond 5 (8.2 ka BP) events, up to the beginning of the Atlantic period when values were lower than today's (Rodrigues et al., 2009; Salgueiro et al., 2010; dos Santos, 2010).

Holocene river water temperature records from several cores and particularly one at the superior area of the estuary, at Vila Franca de Xira (VFX—38° 56' 24" N, 8° 56' 19" W), have shown a decreasing temperature trend from the beginning of the Holocene, in agreement with records from other cores in the Tagus prodelta, like D13882 (38° 38.07' N, 9° 27.25' W) (Rodrigues et al., 2009),

showing that water coming from the river is generally colder than water in the Atlantic coast where the river drains to (Rodrigues et al., 2009; dos Santos, 2010).

Subtle variations in water surface temperature in Vila Franca de Xira (around 1–2 °C) at around 11.3–11.1, 10.5–10, 7.8, 6.6, 5.8, 5, 4.5, and 1.4 to 0.8 ka BP coinciding with the so-called Bond cool events in North Atlantic (Bond, 1997; dos Santos, 2010 along with decreased water surface temperatures led to dryer atmospheric conditions (Cacho et al., 1999; Frigola et al., 2007; McDermott et al., 2001; Rasmussen et al., 2006). Notwithstanding, when comparing water surface temperature values in the Tagus with the maximums of terrigenous contributions, it is possible to find five coincident events: 10.5, 7.8–7.7, 6.7–6.6, 5.9–5.8, and 5–4.5 ka BP, parallel to cold humid periods and flooding or at least increased activity periods in the Tagus (Benito et al., 2008, Benito et al., 2003; dos Santos, 2010, p. ii; Vis et al., 2010), making the Tagus an ecological niche, with a great concentration of food resources both aquatic and terrestrial (Bicho, 2009; Bicho et al., 2010).

Materials and methods

Sample

The majority of fish remains ($N = 5410$ from layers 1 to 4 until the 2014 excavations) consists of vertebral remains, with very few cranial elements ($N = 22$; Table 4) including otoliths from only one species: *A. regius* (Meagre) ($N = 35$). The majority of the otoliths were recovered from layer 1 (1 and 1B, $N = 26$), although they were also present in some of the other layers (layer 2 = 7, layer 4 = 1). This is probably due to *A. regius* otolith characteristics, being generically more robust than those of other species (Assis, 2000; Gabriel et al., 2012; Prista et al., 2009) and therefore better equipped for resisting varied post-depositional conditions. Other *A. regius* bones are also common in layer 1, but they are present in some other layers in larger numbers (e.g., layer 2 with $N = 89$ remains vs. $N = 55$ remains in layer 1 and a total of $N = 163$ through all layers).

We examined 15 *A. regius sagittae* otoliths recovered from layer 1. They were collected both by sieving of the 10-l buckets recovered in the field and as piece plotted elements (> 2 cm) with a total station.

They were stored in plastic zip lock bags and washed with cold tap water following transportation to the laboratory.

Otoliths were, as previously mentioned, chosen by their chronostratigraphic context from layer 1, the last Mesolithic occupation of Cabeço da Amoreira. The majority of the otoliths were juveniles, with two exceptions (2072 and 1982).

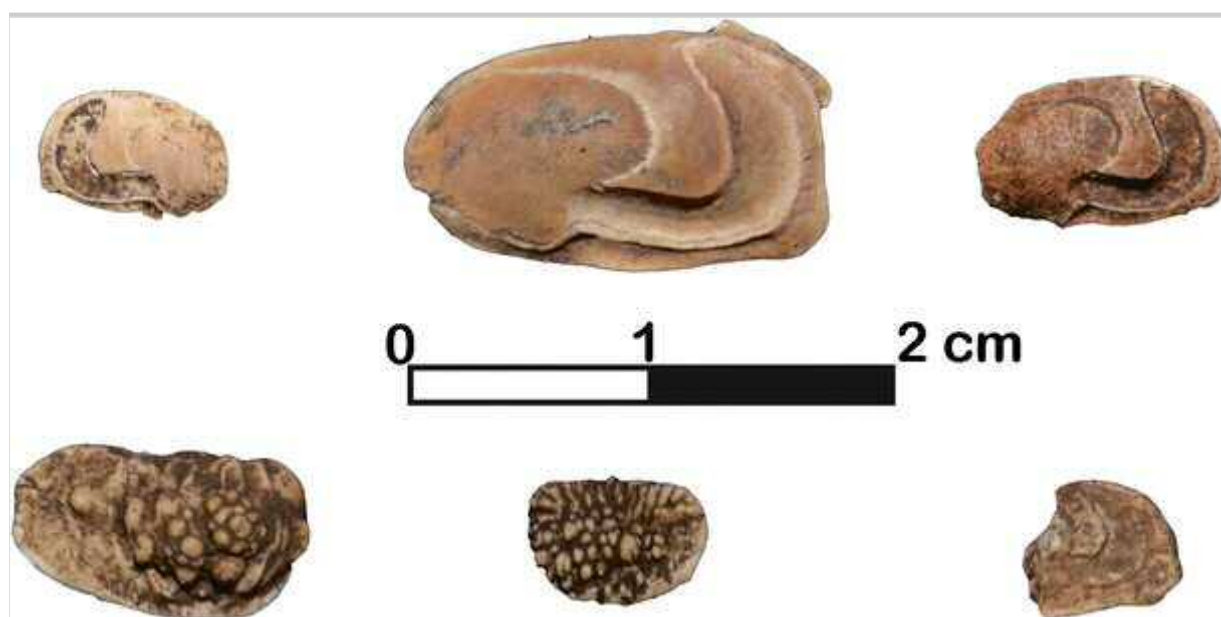
The two larger ones were sampled respectively 52 and 58 times along annual growth increments to ensure that there was a proxy/reference pattern for isotope values for the time frame and area that would allow a clearer interpretation of results from the smaller ones, sometimes less than 1-year-old.

Sampling preparation

The fact that these are archaeological samples, not always in pristine conditions (i.e., surface damage, edge damage etc.), made it necessary to adapt known methodologies (Prista et al., 2009) (Fig. 4).

Fig. 4

Examples of otolith conservation at Cabeço da Amoreira



Firstly, *A. regius* otoliths are too thick to directly use age determination with entire otoliths. Secondly, the need to sample for isotope analysis led to the necessity of establishing an ideal methodology for sectioning them. That decision was made based on a few parameters: (1) which plane (i.e., ventral-dorsal vs anterior-posterior) offered the best reading possibility, that is, a bigger portion of preserved edge (this being essential for seasonal interpretations)?; (2) which plane offered a larger area for sampling?

The next stage was embedding in polyester casting resin. We decided that complete embedding was a better method than partially embedding in clear adhesive on to standard microscope slides (Prista et al., 2009) since it would make the otoliths more stable and robust for sectioning and drilling and the required softening of the solid adhesive sticks over a hot plate before embedding

would risk further damage to the otoliths. Embedded samples were allowed 48 h to dry before sectioning.

Sectioning was accomplished with a low speed saw equipped with a fine-grit diamond-impregnated grinding wheel (3 mm thickness) and aimed to cut as close to the center of the otolith as possible.

Grinding and polishing were executed to remove coarse scratches that could make reading of the *annuli* more difficult. The embedded otoliths were ground using a sequence of coarser to finer carborundum paper on a rotor with running water and were finally polished with a 3- μ m diamond paste, also on a rotor equipped with a velvet surface (Butler et al., 2009; Scourse et al., 2006).

The blocks that resulted from sectioning were then observed both under a stereomicroscope and a metallographic microscope (under transmitted and/or reflected light) to determine the readability of the samples for future sampling and ascertain the necessity of making a thin section as an image guide for drilling and estimate of age. Estimate of age (although not a primary goal of this investigation) was made under both transmitted and reflected light and, at this point, had only one reader and tree readings in separate days and aleatory order of sample reading. Also with this purpose, an acetate peel replicate from two otoliths was produced after etching with 0.1 M HCl for 15 and 30 min. It was concluded that thin sectioning would not improve or help significantly the reading/interpretation of annuli and would instead make it more time consuming and expensive. These otoliths were then re-polished prior to extracting the powder for isotope analysis.

AQ34

Sample powder (minimum mass of $\sim 50 \mu\text{g}$) was then milled with a New Wave microdrill using a carbide burr (300 μm). Rotation was kept at 8% (equivalent to $\sim 2967 \text{ rpm}$) to keep the aragonite to calcite conversion to a minimum and the samples were stored in low absorption weighting paper to avoid loss due to electrostatic charge (Foster et al., 2008).

AQ35

Isotope analysis

Stable isotope composition of the sample powder was measured on a Thermo MAT253 dual inlet mass spectrometer coupled to a Kiel IV carbonate preparation device at Cardiff University. Results are reported per mil (‰) notation on the Vienna-Pee Dee Belemnite (VPDB) scale. The 1-sigma external precision of an in-house carbonate standard was better than $\pm 0.05\text{‰}$ for $\delta^{18}\text{O}$ during the period that the samples were analyzed. Sample weight allowed

running a number of duplicates in some of the samples, generally with good reproducibility due to their quality (i.e., powder was homogeneous). Precision of replicate samples is $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}$.

Diagenesis analysis

DAalysis was conducted on the otoliths embedded in epoxy to assess the preservation vs alteration of the otolith samples, in order to confirm whether or not the $\delta^{18}\text{O}$ data were reliable for reconstructing a seasonality pattern during Mesolithic in Central Portugal. Testing diagenesis has been done in other occasions and the potential of a multitude of techniques as discussed (Cook et al., 2015; Disspain et al., 2011; Dufour et al., 2000).

1. Raman spectroscopy (microspectrometry)

μ -Raman analysis was performed to identify the mineralogical composition of the otoliths and especially to distinguish aragonitic (well-preserved) from calcitic (diagenetically altered) otoliths. Analysis was conducted using a Horiba-Jobin Yvon XploRA confocal Raman spectrometer coupled to an Olympus BX41 microscope equipped with a digital camera. A pure silicon standard was used to calibrate the wavelength scale prior to any analysis. Raman spectra were acquired using LabSpec software, using the following experimental conditions: laser source $\lambda = 785\text{ nm}$; laser objective of $\times 50$, filter 50%; 1200 T; 699.88 cm^{-1} ; and acquisition, 1, 5, and 20. Spectra deconvolution was performed using LabSpec (V5.78). The identification of compounds was made in good agreement with the literature (White, 2009), spectral ID, and our own reference spectra (Kremer).

AQ36

Two to three sample spots were analyzed per sample. The determination of aragonite versus calcite was based on the following vibrational bands: aragonite ($155, 207, 704, 1085\text{ cm}^{-1}$) and calcite ($158, 282, 713, 1086\text{ cm}^{-1}$) (White, 2009). Therefore, the presence of a peak at 207 cm^{-1} especially was checked in order to assess for the preservation of the aragonite.

2. Laser ablation inductively coupled plasma mass spectrometry

AQ37

Trace elemental composition of one sample (2072) was analyzed by LA-ICP-MS, using an Agilent 8800 ICP-MS Triple Quad coupled to a CETAC LSX-213 G^{2+} laser ablation system. Operating conditions are described in Table 5. The equipment was calibrated and tuned prior to the analysis with the glass certified reference material NIST 612. Elemental fractionation was monitored and

optimized using $^{238}\text{U}/^{232}\text{Th}$ ratio ($\cong 101\%$) and oxide formation was evaluated using $^{248}\text{ThO}/^{232}\text{Th}$ ratio ($< 0.3\%$). Li, Na, Mg, Ca, Mn, Fe, Co, Cu, Zn, Sr, Y, Ba, La, Ce, Nd, Sm, Yb, Pb, Th, and U were screened and analyzed.

Table 5

Operating conditions for the LA-ICP-MS analyses

Acquisition mode	TRA (time resolved analysis)
Scan type and tune mode	MS/MS in no gas mode
Plasma parameters	
RF power	1550 W
RF matching	1.3 V
Sample depth	4 mm
Dilution gas (Ar)	0.65 L/min
Plasma gas (Ar)	15 L/min
Dwell time and measure isotopes	
2 ms	^{44}Ca
5 ms	^{43}Ca
10 ms	^7Li , ^{23}Na , ^{24}Mg , ^{39}K , ^{55}Mn , ^{63}Cu , ^{66}Zn , ^{88}Sr
20 ms	$^{56,57}\text{Fe}$, ^{59}Co , ^{89}Y , ^{137}Ba , ^{139}La , ^{140}Ce , ^{146}Nd , ^{147}Sm , ^{172}Yb , ^{208}Pb , ^{232}Th , ^{238}U

Prior to the analysis by LA-ICP-MS, a pre-ablation of the sample was performed in order to clean the sample surface and thus avoid possible handling contaminations.

Mapping the distribution of these elements within the otolith sample was done ablating 30 lines (around 5000 μm length), 20 μm between lines (to prevent contamination between lines). Conversion of intensities in cps to images was done using iQuant2 software, developed by Institute of Technology of Tokyo and University of Kyoto.

Quantification analysis was done by spot analysis. Ninety-four spots of 50 μm were ablated along the cross section of the otolith. Total sample ablation time was set to 40 s, including 10 s of blank acquisition and 10 s of wash out. Cps intensities were converted to part per million concentrations with Glitter® Software, using CaO as internal standard and previously converted from Ca

concentrations obtained by SEM-EDS. A synthetic calcium carbonate (USGS MACS3) was used as an external standard in order to correct for instrumental drifts. All the laser ablation operational conditions are summarized in Table 6.

Table 6
Laser ablation conditions

	Mapping conditions	Quantification conditions
Laser energy	65%	65%
Spot size	50 μm	50 μm
Repetition rate	10 Hz	20 Hz
Method selection	Line scan (30 lines ≅ 5 mm)	Single point (94 spots)
Space between lines	20 μm	—
Scan rate	20 μm/s	—
Burst count	—	400
He carrier flow	1 L/min	1 L/min

Results

All the examined otoliths showed clearly marked banding patterns, even though the majority were juvenile specimens. Two of the observed otoliths were from fairly large and older animals (2072 = + 33 and 1982 = + 12 see Table 6), although far from the maximum registered in modern specimens (i.e., ~ 2 m and 50 kg of weight) (Chao and Trewavas, 1990; Pollard et al., 2015) (see Table 6 for age and seasonal estimate).

A clear annual temperature cycle was visible in all otoliths, especially those older than 1 year (Fig. 5) and the last increment provided estimated seasonality of death through $\delta^{18}\text{O}$ values (Figs. 6 and 7); in other words, negative—lighter—values tend to represent higher temperatures, common from spring to late summer or autumn in analyzed latitudes, and positive values, heavier, tend to represent lower temperatures, common through autumn and winter. The variation in the $\delta^{18}\text{O}$ values throughout the fish’s life, as represented in the graphics, shows the temperature variations expected with changing seasons and the last value could therefore provide an estimation of season of capture, which in general seems to indicate the majority of captures occurred between spring and late summer/autumn.

Fig. 5

$\delta^{18}\text{O}$ seasonal variations in analyzed specimens

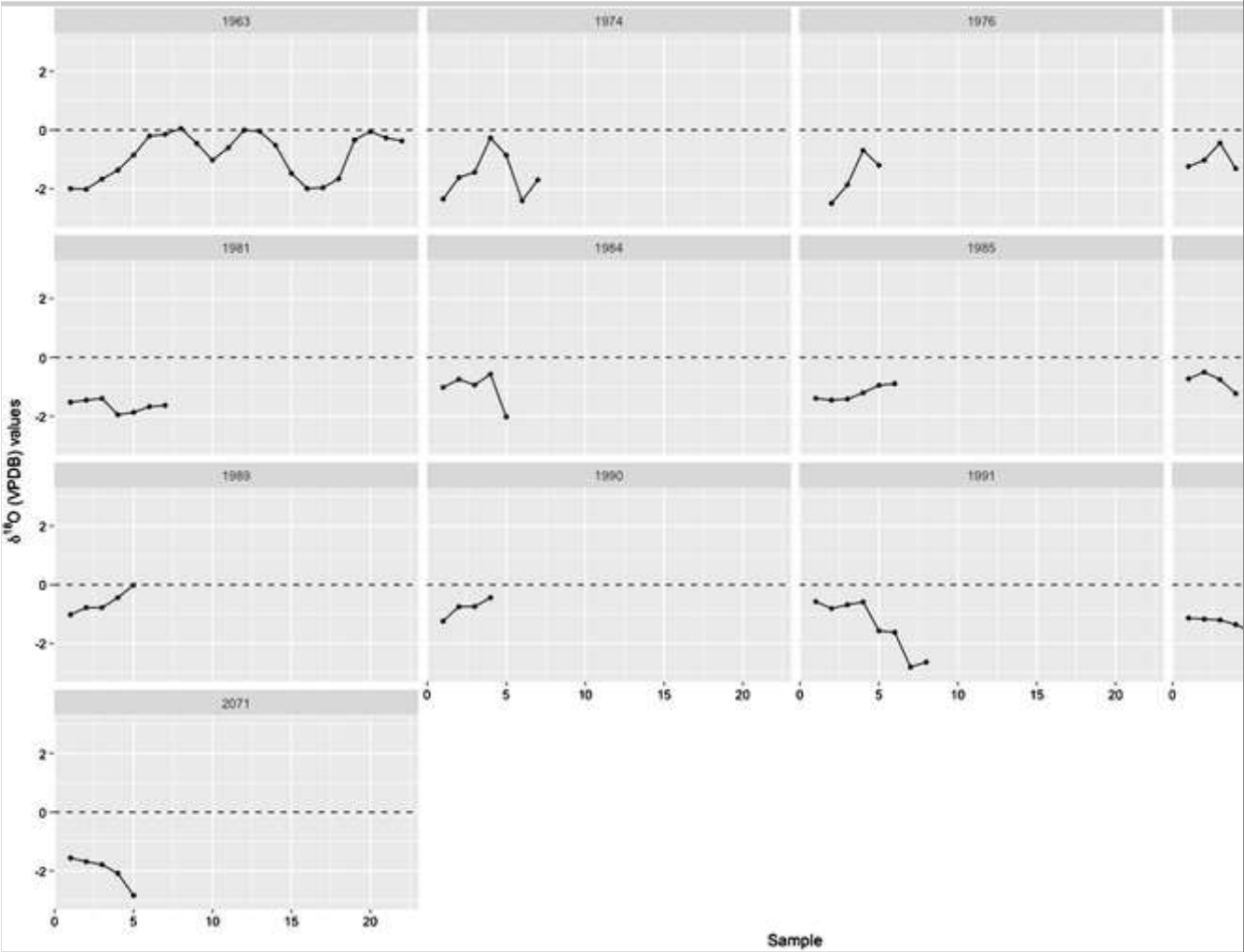


Fig. 6
 $\delta^{18}\text{O}$ results for sample 1982 used has proxy (the last increment was not sampled in both cases has its conservation was not completely clear)

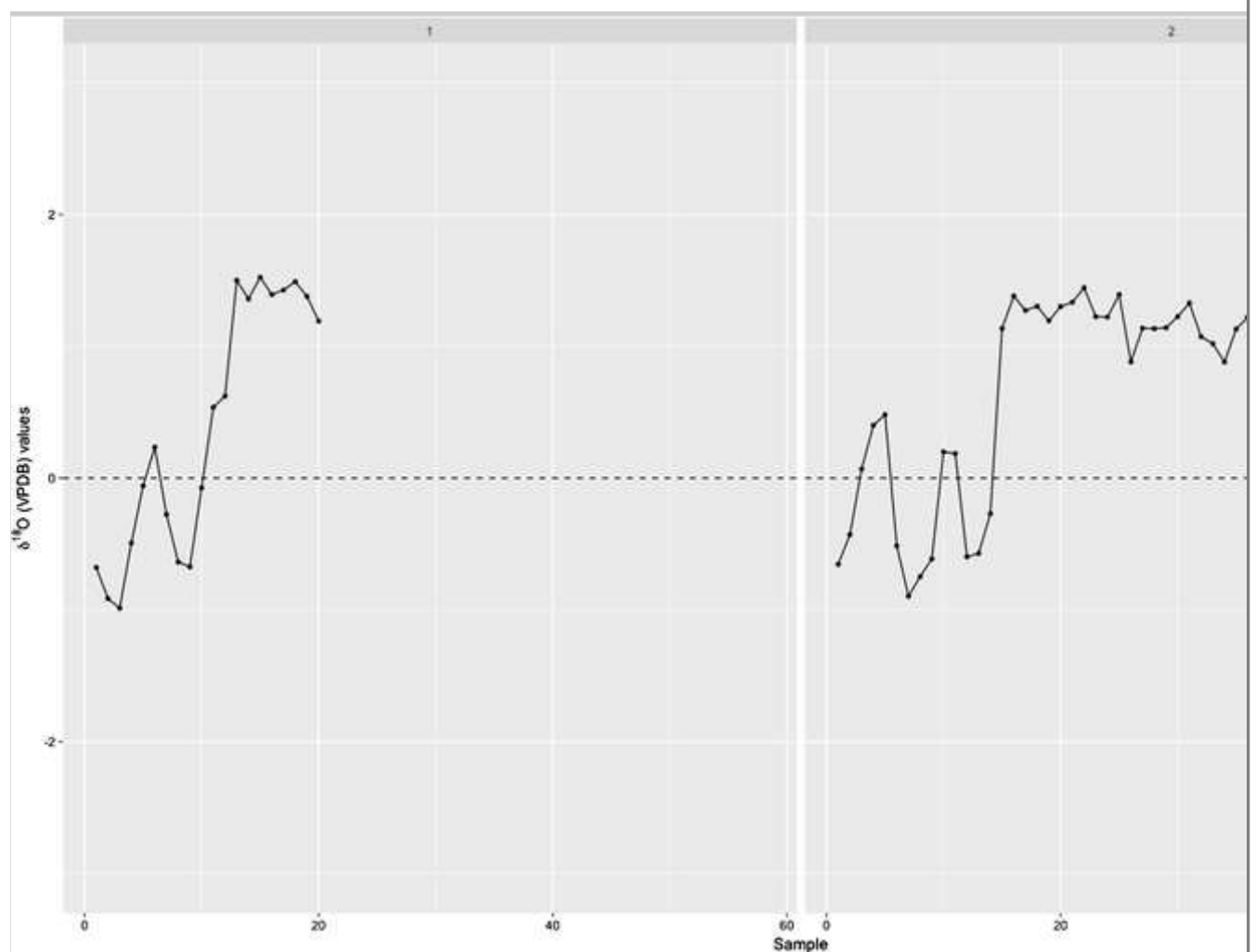
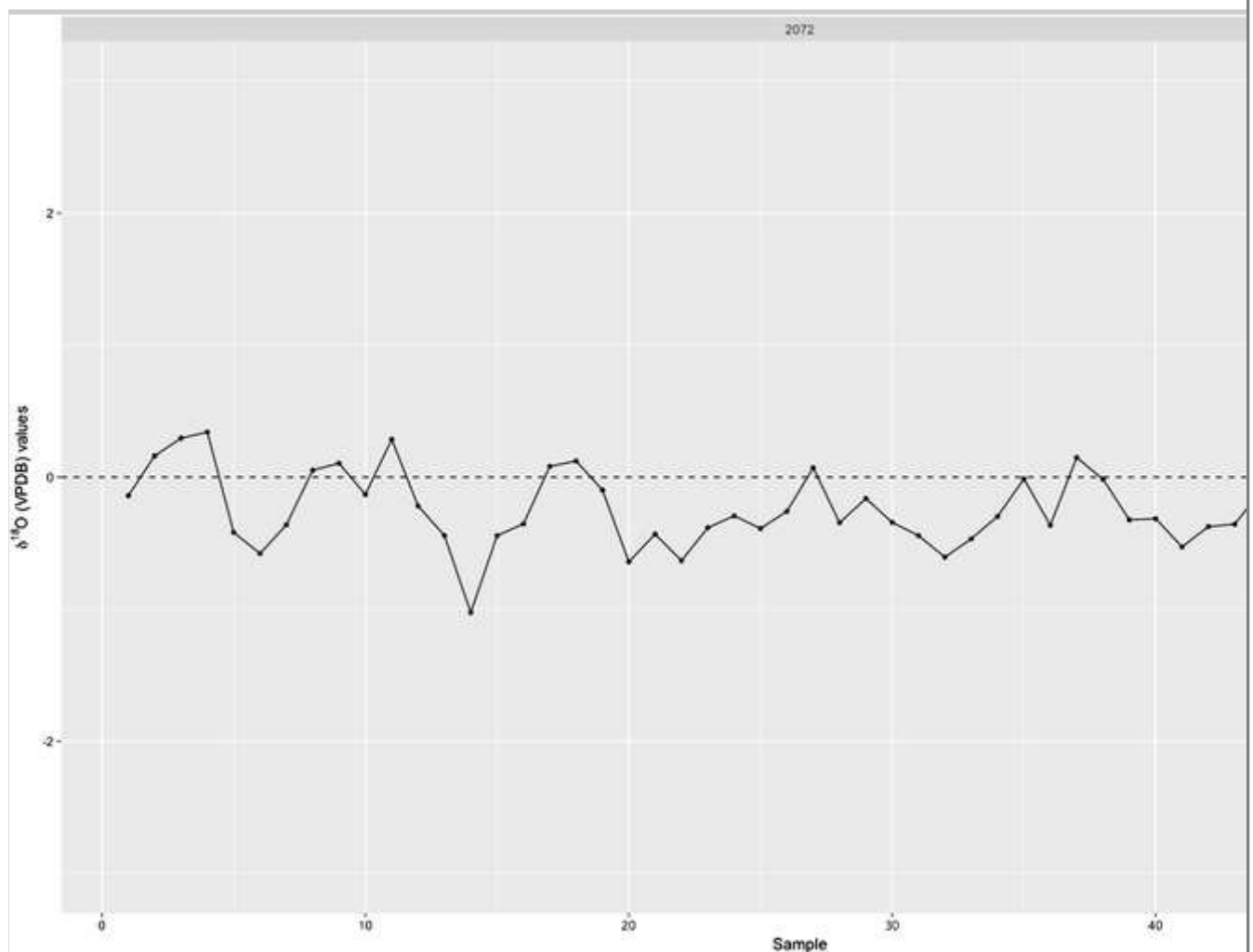


Fig. 7

$\delta^{18}\text{O}$ results for the two samples of otolith 2072 (both halves) used has proxy (the last increment was not sampled in both cases has its conservation was not completely clear)



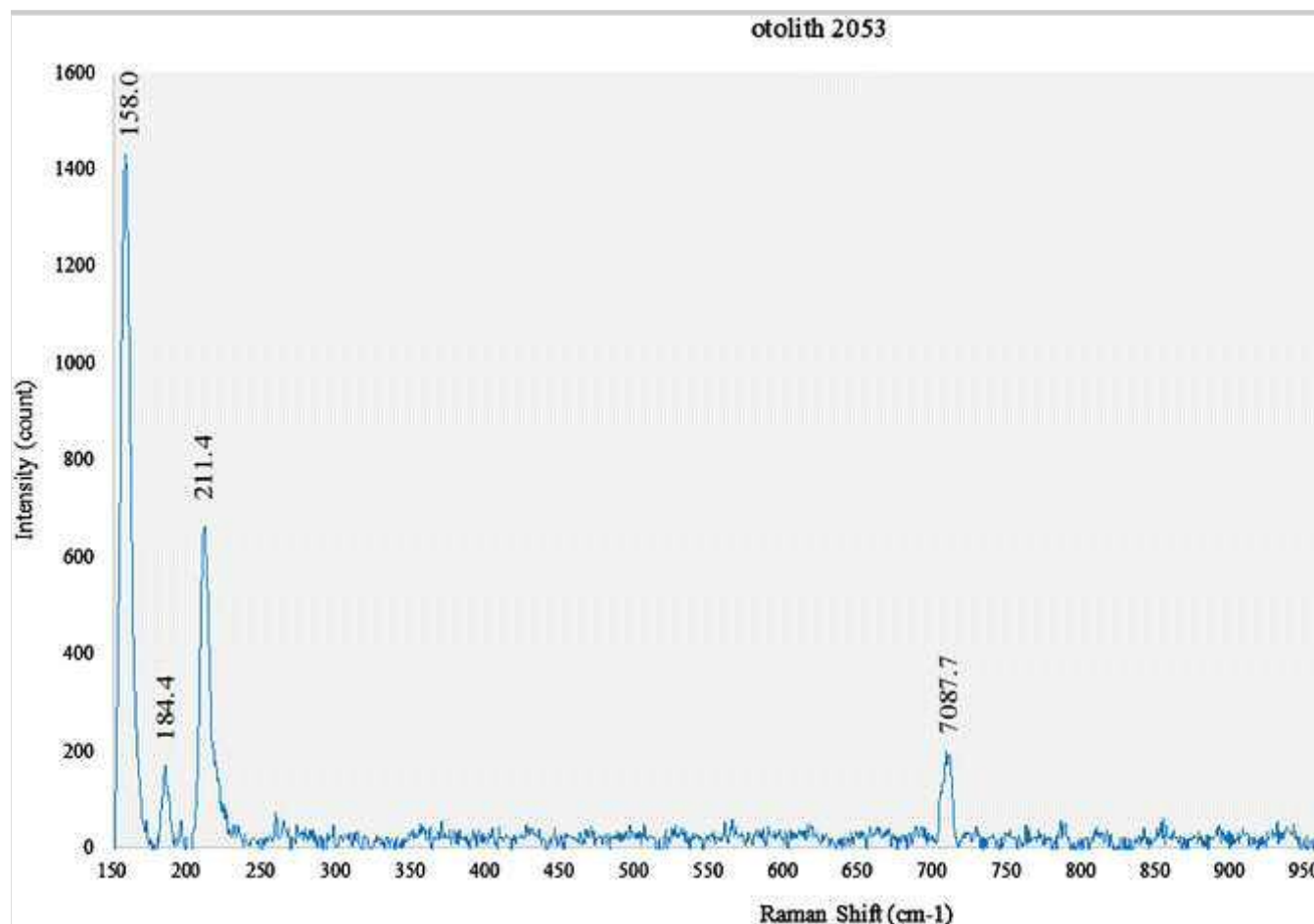
1. Raman spectroscopy—mineralogical composition of the otoliths

AQ38

The spectra obtained using μ -Raman, for all 15 otolith samples analyzed, show a consistent pattern with presence of aragonite and no indication of calcite (Fig. 8).

Fig. 8

μ -Raman spectra obtained for otolith sample 2072. Aragonite-vibrational bands at 155, 207, 704, and 1085 cm^{-1} . Calcite vibrational bands at 158, 282, 713, and 1086 cm^{-1} not detected



2. Laser ablation ICP-MS—trace elemental composition of the otoliths

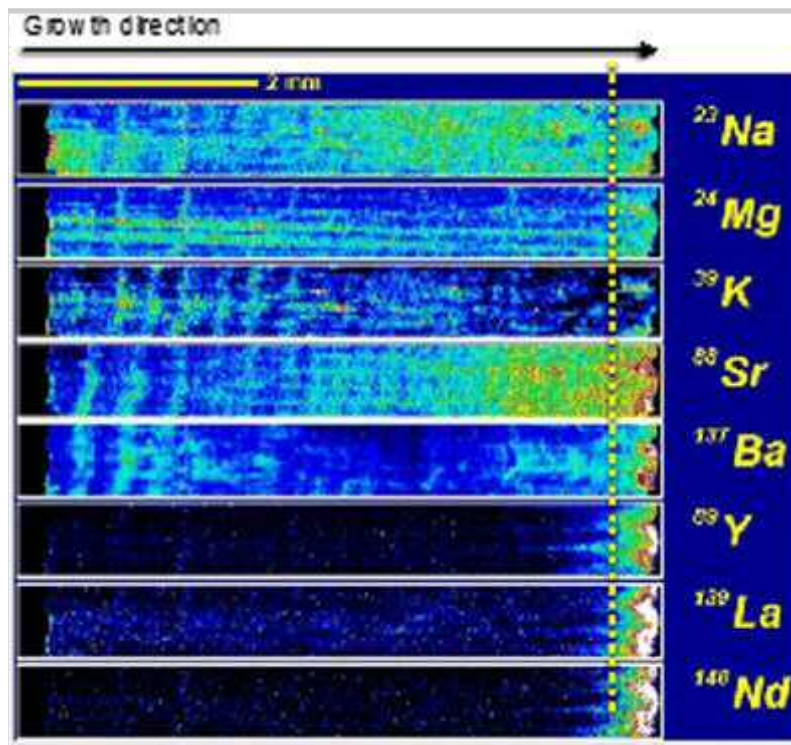
The elemental mapping and quantification of trace elemental content of the sample 2072, performed by LA-ICP-MS, suggests that the outer edge yields higher concentrations of rare earth elements (Y, La, Ce, Nd, Sm, and Yb) compared to its internal part where the concentrations of these elements do not exceed 18 ppbs (Fig. 7 and Table X). This slight enrichment does not alter the $\delta^{18}\text{O}$ values.

AQ39

Other elements such as Na, Mg, K, Sr, and Ba seemed to reflect the growth incremental pattern of the otoliths (Fig. 9).

Fig. 9

Elemental distribution of some selected elements performed by LA-ICP-MS

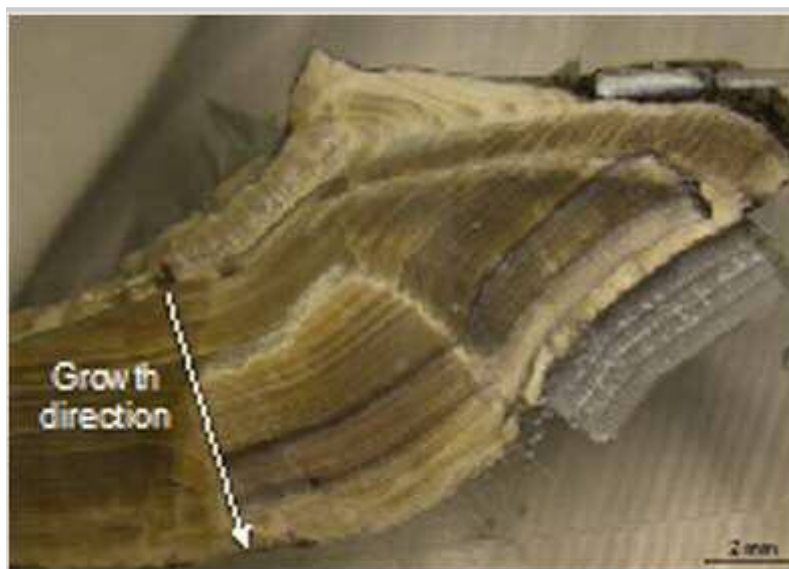


Discussion and conclusions

Discussion of whether or not occupation dynamics are dependent on the diversity and/or availability of animal resources is not new (Dupont, 2016) but the seasonality and duration of these particular occupations are rarely discussed in detail (i.e., 19% of published papers on European shell middens. See Dupont, 2016, p. 4), contrary to the permanence of this occupation, which seems to be more frequently discussed (e.g., like Cabeço da Amoreira, used for over c. 200 years, although maybe not permanently throughout the year) Fig.10.

Fig. 10

Lasered otolith (2072)



AQ40

In some sites, human occupation does not necessarily coincide with periods of accessibility to food resources (Dupont, 2016). That does not seem to be the case with Cabeço da Amoreira. There is not enough evidence at this point to be confident about the existence of specialized activity camps, since further investigation of the other surviving shell middens is required.

Although $\delta^{18}\text{O}$ results seem to generically frame the date of collection/death (Fig. 5 and Table 7), it is still difficult to investigate the occupation mode (i.e., duration and type of occupation) and seasonality because many factors are involved in what is available to construct seasonal use of resources' and spaces' models (e.g., Dupont 2016 or Bicho, 2009, Bicho et al., 2011, 2013). These questions have still not been systematically investigated in the Atlantic shell middens (with some exceptions where researchers used up to 12 different criteria to ascertain season of occupation) (Dupont, 2016). Nevertheless, the large array of shell midden investigations, in the majority of cases, contributed to hinder a clear notion of how/when these populations were occupying these shell middens—assuming there is a pattern—either locally/regionally or more generically. The best approach seems to be to first start at the scale of an archaeological site and only then compare between them as suggested by Dupont (2016) Table 8.

Table 7

Cabeço da Amoreira otolith data

Otolith I.D.	Provenance	Age at death	Inferred season at death** AQ42
2072	1B.2	+ 33	— ^a
1982	1.3	+ 12	— ^a
1963	2.4	~ 2	Spring
1976	1.2	< 1	Spring/late summer?
1974	1.?	2	Spring
1984	1B.3	~ 1	Summer

Seasons were distributed as follows: March–April–May (spring), June–July–August–September (summer), October–November (autumn), and December–January–February (winter)

These otoliths were used as proxies to frame juvenile data and were not sampled to the last ring. 2072's last ring was not completely preserved not allowing a sufficient sample

Otolith I.D.	Provenance	Age at death	Inferred season at death** AQ42
1978	1.3	< 1	Late spring/summer
1990	1.2	< 1	Autumn
1991	1B.1	< 1	Summer
1981	1.1	~ 1	Late summer
1986	1.2	< 1	Late spring/summer
1985	1B.2	< 1	Late summer/autumn
2071	1B.3	< 1	Summer
1989	1.2	< 1	Autumn
2051	1B.3	~ 1	Summer
Seasons were distributed as follows: March–April–May (spring), June–July–August–September (summer), October–November (autumn), and December–January–February (winter)			
^a These otoliths were used as proxies to frame juvenile data and were not sampled to the last ring. 2072's last ring was not completely preserved not allowing a sufficient sample			

Table 8

Ranges of concentrations in the different preserved areas of the otolith sample 2072

	Diagenetically altered	Preserved
%		
Ca	37–42	37–46
Ppm		
Na	915–1130	922–1939
Mg	18–34	10–26
Mn	0.228–8.25	0.043–4.84
Fe	70–92	34–69
Sr	2503–3253	1080–2981
Ba	9–22	0.7–37
Ppb		
Co	30–268	13–92
Cu	157–469	65–1710

	Diagenetically altered	Preserved
Zn	137–407	76–1480
Y	117–1690	4–46
La	12–1490	0.3–13
Ce	12–575	0.2–12
Nd	13–1380	1.7–13
Sm	8–266	3–8
Yb	13–72	2–18
Pb	10–37	12–120
Th	2–50	0.8–7
U	18–36	1.4–136
Li	<detection limit	<detection limit

AQ41

In order to address seasonality, in this paper, we used the case study of the archaeological site of Cabeço da Amoreira. The Cabeço da Amoreira shell midden has been the object of a number of studies that are relevant to the investigation of seasonality: (1) sclerochronology and isotope analysis (this study and Dias et al., unpublished on rays and sharks sclerochronology); (2) microstratigraphy records (Aldeias and Bicho, 2016); spatial analysis and site formation (Bicho et al., 2010, in press; Bicho and Gonçalves, 2016.; Conyers et al., n.d.; Dias et al., 2012; Gonçalves, 2009); (3) faunal remains analysis (Detry, 2007; Dias et al., 2016, Dias et al., 2015; Dupont, 2016; Dupont et al., 2009); (4) lithics analysis (Jesus et al., 2010; Marreiros et al., 2015, n.d.); (5) chronology (Bicho et al., 2013); (6) biological anthropology (Cunha et al., 2003; Cunha and Umbelino, 1995); (7) archaeology of death (Figueiredo, in press; in press(a), 2015; Peyroteu- Stjerna, 2016); (8) human remains isotopes (Umbelino, 2006); and (9) paleobotanical research (Monteiro, 2011; Monteiro and Zapata, n.d.).

AQ43

AQ44

Data supports the suggestion of a prolonged human occupation of the site but not necessarily a permanent or continuous one. Several suggestions have been made that these shell middens (both in Muge and Sado) indicate a sedentary or semi-sedentary occupation (Gutiérrez-Zugasti et al., 2011; Rolão, 1999). However, micromorphology data shows evidence of a likely geogenic hiatuses in the accumulation of the shellmound occupations, compatible with site abandonment

periods (Aldeias and Bicho, 2016, p. 546) which (based on Bayesian modeling of ^{14}C dates) lasted no longer than 50 to 100 years in Muge (Bicho et al., 2013). It is important to add that the micromorphology data are derived from sample areas rather than from the full site and a more thorough micromorphological study is required to confirm these conclusions for the whole site.

Data from bird remains, contrary to the data from fish remains, seem to suggest winter occupation of the site, indicated especially by the presence of several wintering species, although also including *H. himantopus*, which is only present from spring to autumn (see Detry, 2007 for the list of wintering species in the Muge shell middens).

The $\delta^{18}\text{O}$ values for otoliths from Cabeço da Amoreira clearly show seasonal changes (Fig. 9), ranging from heavier values during the winter to lighter values in summer. However, as *A. regius* may move seasonally between areas with different freshwater content (they may enter estuaries in spring or prey on schools of mugilids all year round), the seasonal variability observed may also to some extent reflect changes in salinity of the waters the fish inhabit and as such both temperature and salinity could increase the seasonal $\delta^{18}\text{O}$ range (i.e., warm/fresher vs cold/salty). This could lead to complications in the interpretation of the seasonal temperature signal, especially since even when *A. regius* do not enter estuaries, they live in waters with variable freshwater influence (Hufthammer et al., 2010), migrating northward and southward along the Portuguese Atlantic coast (Prista, 2013).

However, although isotopic variability should be expected in areas directly affected by inflow of river water, $\delta^{18}\text{O}(\text{H}_2\text{O})$ seawater can generally be assumed to range from c. + 0.2 to 0.8‰ in surface or intermediate water and c. + 0.9 to c. + 1.4‰ in deep waters (Iacumin et al., 1992), so that $\delta^{18}\text{O}$ values should be lighter for periods in which *A. regius* are in estuaries, which in this case coincides with negative values as a consequence of temperature.

AQ45

In terms of possible alteration of results due to taphonomical processes, mineralogical analysis of the otolith samples performed using μ -Raman showed that both analyzed otoliths preserved their pristine aragonitic composition. However, this does not preclude any other diagenetic process that might have modified the biological composition of the otolith. In order to assess the preservation of the geochemical composition of the otolith, LA-ICP-MS analysis was used for mapping intensities of Ca, Sr, Ba, Pb, Fe, Cu, Zn, Co, U, Th, Nd, Ce, La, and Y and seeing whether their distribution pattern might relate to post-burial transformations. Although the distribution pattern of Y, La, and Nd

obtained using LA-ICP-MS analysis showed that the outer edge of the sample might have become slightly enriched in these elements during burial, the part of the otolith sampled for measuring oxygen and carbon isotopes seems not to have been subject to taphonomic contamination. Therefore, the combination of mineralogical and geochemical data suggest a preservation of the otolith against diagenetic processes and therefore confirm that the isotopic composition should reflect the *in vivo* composition and can be used for reconstructing fish exploitation strategies adopted by the Mesolithic population of Cabeço da Amoreira.

Seasonality results from Cabeço da Amoreira's layer 1 *A. regius* otoliths are in agreement with seasonal abundance of this species in the Tagus estuary. Modern fisheries investigations indicate that *A. regius* concentrates in the estuary from May through September, migrating along Portuguese coastal areas in the autumn-winter months (Prista, 2013). The targeting of this species in the Muge area (or more generically the Tagus estuary) was probably determined by the species regular annual migration cycle, from the estuary to the coast and vice versa as it is in the present day.

In addition, the stratigraphic distribution of the species, with the greatest concentration being on layer 1, could indicate either a species targeting/preference or a consequence of taphonomic degradation with less well-preserved otolith remains in other layers.

All these data might suggest a seasonal pattern of gathering activities. Although still heavily dependent on terrestrial resources (especially rabbits and red deer *vide* Detry, 2007 and Dias et al., 2016 and Umbelino, 2006 for isotope results in human remains), this human group(s) have based their subsistence on a seasonal round of activities with a transient population, in family groups (for further discussion on this see Gonçalves et al., 2014), involved in seasonal gathering and fishing/hunting. These activities could (and must have been) dependent on the seasonal abundance of resources in the region.

AQ46

Further seasonality investigations must be carried out to validate and further contribute to these results. These preliminary results and the method here established for the analysis of these types of archaeological remains and sites, however, show the potential of these investigations, suggesting that an investment should be made in creating both archaeological and modern reference collections.

The quantity of shell remains at this site and their differential preservation indicate great potential of the site as an example of the usefulness of archaeological isotopic analysis which, although increasingly frequent, is still far from ideal. Analysis of age of death in vertebral and other fish remains can also make a significant contribution to seasonality studies, although this is severely limited by taphonomical issues; in particular, the preservation state of the last increment needs to be taken into account. This method can also be limited by subjectivity (Casselman, 1983; Wheeler and Jones, 2009).

Acknowledgements

AQ47

The National Portuguese Foundation for Science and Technology (Portugal) funded the 2008-2011 Last Hunter-gatherers of the Tagus Valley–The Muge Shell Middens (PTDC/HAH/64185/2006)” project and the 2011-2014 “The last hunter-gatherers of Muge (Portugal): the origins of social complexity (PTDC/HIS- ARQ/112156/2009)” project whose P.I. is Nuno Bicho.

The Archaeological Institute of America that funded the “Mesolithic shell midden exploitation: Sclerochronology analysis from the Cabeço de Amoreira (SW Iberia, Portugal)” project, through the Archaeology of Portugal Program given to Rita Dias.

The ICArEHB-Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour is acknowledged, in the University of Algarve, for partially funding the isotope analysis with funding from FCT (UID/ARQ/04211/2013). We would also like to thank Stella Alexandroff for her invaluable help in the Sclerolab and Professor Chris Richardson for his time and advice in establishing a methodology, both at the University of Bangor, Wales, UK.

References

AQ48

AQ49

Aldeias V, Bicho N (2016) Embedded behavior: human activities and the construction of the Mesolithic Shellmound of Cabeço da Amoreira, Muge, Portugal. *Geoarchaeology* 31(6):530–549. <https://doi.org/10.1002/gea.21573>

Andrus CFT (2011) Shell midden sclerochronology. *Quat Sci Rev* 30(21-22):2892–2905. <https://doi.org/10.1016/j.quascirev.2011.07.016>

Araújo, A.C., Almeida, F., 2013. Barca do Xerez de Baixo, um testemunho invulgar das últimas comunidades de caçadores colectores do Alentejo interior, in: Araújo, A.C., Almeida, F. (Eds.), *Memórias do’Odiana*. 2ª Série

Estudos Arqueológicos Do Alqueva. Câmara Municipal de Beja, Beja, pp. 327–332

Arnaud JM (1986) O Cabeço das Amoreiras. S Romão do Sado Informação Arqueol 7:80–82

AQ50

Arnaud JM (1987) Os concheiros mesolíticos dos vales do Tejo e do Sado: semelhanças e diferenças. Arqueologia 15:53–64

Arnaud JM (1993) O Mesolítico e a neolitização. Balanço e perspectivas. In: Carvalho GS, Ferreira AB, de Senna-Martinez J (eds) O Quaternário Em Portugal. Balanços E Perspectivas. Edições Colibri, Lisboa, pp 173–184

AQ51

Arnold JE (1996) The archaeology of complex hunter-gatherers. J Archaeol Method Theory 3(1):77–126. <https://doi.org/10.1007/BF02228931>

Assis, C. A. da S. 2000. Estudo Morfológico dos Otólitos Saggita, Asteriscus e Lapillus de Teleósteos (Actinopterygii, Teleostei) de Portugal Continental. Sua Aplicação em Estudos de Filogenia Sistemática e Ecologia. Ecologia. Faculdade de Ciências da Universidade de Lisboa

Athayde A (1940) Novos esqueletos humanos dos concheiros mesolíticos de Muge. In: Português CDM (ed) Lisboa. Comissão Executiva dos Centenários, Lisboa, pp 627–651

Bard E, Arnold M, Maurice P, Duprat J, Moyes J, Duplessy J-C (1987) Retreat velocity of the North Atlantic polar front during the last deglaciation determined by ^{14}C accelerator mass spectrometry. Nature 328(6133):791–794. <https://doi.org/10.1038/328791a0>

Beamish, R.J., McFarlane, G.A., 1983. Validation of age determination estimates: the forgotten requirement, in: Prince, E.D., Pulos, L.M. (Eds.), Proceedings of the International Workshop on Age Determination of Oceanic Pelagic Fishes: Tunas, Billfishes, and Sharks. National Oceanic and Atmospheric Administration and U.S. Department of Commerce, Miami, pp. 29–34

Begg GA, Campana SE, Bowler AJ, Suthers IM (2005) Otolith research and application: current directions in innovation and implementation. Mar Freshw Res 56(5):477–483. <https://doi.org/10.1071/MF05111>

Benito G, Sopena A, Sánchez-Moya Y, Machado MJ, Pérez-González A (2003) Palaeoflood record of the Tagus River (Central Spain) during the Late Pleistocene and Holocene. *Quat Sci Rev* 22(15-17):1737–1756.
[https://doi.org/10.1016/S0277-3791\(03\)00133-1](https://doi.org/10.1016/S0277-3791(03)00133-1)

Benito G, Thorndycraft VR, Rico M, Sánchez-Moya Y, Sopena A (2008) Palaeoflood and floodplain records from Spain: evidence for long-term climate variability and environmental changes. *Geomorphology* 101(1-2):68–77. <https://doi.org/10.1016/j.geomorph.2008.05.020>

Bicho N (1994) The end of the Paleolithic and the Mesolithic in Portugal. *Curr Anthropol* 35(5):664–674. <https://doi.org/10.1086/204328>

Bicho N (2003) A importância dos recursos aquáticos na economia dos caçadores-recolectores do Paleolítico e Epipaleolítico do Algarve. *Xelb* 4:11–26

Bicho N (2009) Sistemas de povoamento, subsistência e relações sociais dos últimos caçadores-recolectores do Vale do Tejo. *Estud Arqueol Oeiras* 17:133–156

Bicho, N., Gonçalves, C., 2016 Back to the past: the emergence of social differentiation in the Mesolithic of Muge, Portugal, in: The Eighth International Conference on the Mesolithic in Europe will be held in Santander from 13th to 17th September 2010, Cantabrian International Institute for Prehistoric Research. Santander

Bicho N, Haws J (2008) At the land's end: marine resources and the importance of fluctuations in the coastline in the prehistoric hunter–gatherer economy of Portugal. *Quat Sci Rev* 27(23-24):2166–2175.
<https://doi.org/10.1016/j.quascirev.2008.08.011>

Bicho, N., Cascalheira, J., Gibaja, J., Manne, T., Marreiros, J., Mendonça, Carolina, Pereira, T., Regala, F., 2009. Identidade e adaptação: a ocupação humana durante o Plistocénico Final no Algarve Ocidental, in: VII Reunião Do Quaternário Ibérico. Faro, pp. 171–174

Bicho N, Umbelino C, Detry C, Pereira T (2010) The emergence of Muge Mesolithic Shell Middens in Central Portugal and the 8200 cal yr BP cold event. *J Isl Coast Archaeol* 5(1):86–104.
<https://doi.org/10.1080/15564891003638184>

Bicho N, Cascalheira J, Marreiros J, Pereira T (2011) The 2008-2010 excavations of Cabeço da Amoreira, Muge. Portugal Mesolith Misc 21:3–13

Bicho N, Cascalheira J, Marreiros J, Gonçalves C, Pereira T, Dias R (2013) Chronology of the Mesolithic occupation of the Muge valley, central Portugal: the case of Cabeço da Amoreira. *Quat Int* 308–309:130–139. <https://doi.org/10.1016/j.quaint.2012.10.049>

Bicho, N., Pereira, T., Umbelino, C., Jesus, L., Marreiros, J., Cascalheira, J., Gonçalves, C., Detry, C., n.d. The construction of a shell midden: the case of Cabeço da Amoreira, Muge (Portugal). In: The Eighth International Conference on the Mesolithic in Europe will be held in Santander from 13th to 17th September 2010, Cantabrian International Institute for Prehistoric Research. Santander

Bond G (1997) A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science* 278(80):1257–1266. <https://doi.org/10.1126/science.278.5341.1257>

Brewer DJ (1987) Seasonality in the prehistoric Faiyum based on the incremental growth structures of the Nile catfish (Pisces: Clarias). *J Archaeol Sci* 14(5):459–472. [https://doi.org/10.1016/0305-4403\(87\)90032-X](https://doi.org/10.1016/0305-4403(87)90032-X)

Butler PG, Scourse JD, Richardson CA, Wanamaker AD Jr, Bryant CL, Bennell JD (2009) Continuous marine radiocarbon reservoir calibration and the ^{13}C Suess effect in the Irish Sea: results from the first multi-centennial shell-based marine master chronology. *Earth Planet Sci Lett* 279(3-4):230–241. <https://doi.org/10.1016/j.epsl.2008.12.043>

Cacho I, Grimalt JO, Pelejero C, Canals M, Sierro FJ, Flores JA, Shackleton N (1999) Dansgaard-Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures. *Paleoceanography* 14(6):698–705. <https://doi.org/10.1029/1999PA900044>

Campana SE (2001) Accuracy, precision and quality control in age determination, including a review of the use and abuse of age validation methods. *J Fish Biol* 59(2):197–242. <https://doi.org/10.1006/jfbi.2001.1668>

Campana SE, Neilssra D (1985) Microstructure of fish otoliths. *Can J Fish Aquat Sci* 42(5):1014–1032. <https://doi.org/10.1139/f85-127>

Campana SE, Annand MC, McMillan JI (1995) Graphical and statistical methods for determining the consistency of age determinations. *Trans Am Fish Soc* 124(1):131–138. [https://doi.org/10.1577/1548-8659\(1995\)124<0131:GASMFD>2.3.CO;2](https://doi.org/10.1577/1548-8659(1995)124<0131:GASMFD>2.3.CO;2)

Cardoso JL, Rolão JM (1999) Prospecções e escavações nos concheiros mesolíticos de Muge e de Magos (Salvaterra de Magos): Contribuição para a história dos trabalhos arqueológicos efectuados. *Estud. Arqueol. Oeiras* 8:306–357

Casselman, J.M., 1983. Age and growth assessment of fish from their calcified structures—techniques and tools, in: Prince, E.D., Lynn, M.P. (Eds.), *Proceedings of the International Workshop on Age Determination of Oceanic Pelagic Fishes: Tunas, Billfishes, and Sharks*. National Oceanic and Atmospheric Administration and U.S. Department of Commerce, Miami, pp. 1–18

Casteel RW (1976) *Fish remains in archaeology*. Academic Press, London

Casteel, R.W., 2011. Society for American Archaeology Some archaeological uses of fish remains. *Am Antiq* 37, 404–419

Cearreta A, Cachão M, Cabral MC, Bao R, de Jesus Ramalho M (2003) Lateglacial and Holocene environmental changes in Portuguese coastal lagoons 2: microfossil multiproxy reconstruction of the Santo André coastal area. *The Holocene* 13(3):447–458.
<https://doi.org/10.1191/0959683603hl637rp>

Chao LN, Trewavas E (1990) Sciaenidae. In: Quero JC, Hureau JC, Karrer C, Post A, Saldanha L (eds) *Check-list of the fishes: the eastern tropical Atlantic (CLOFETA)*. JNICT/SEI/UNESCO, Paris, pp 813–826

Colonese AC, Troelstra S, Ziveri P, Martini F, Lo Vetro D, Tommasini S (2009) Mesolithic shellfish exploitation in SW Italy: seasonal evidence from the oxygen isotopic composition of *Osilinus turbinatus* shells. *J Archaeol Sci* 36(9):1935–1944. <https://doi.org/10.1016/j.jas.2009.04.021>

Colonese AC, Verdún-Castelló E, Álvarez M, Briz I, Godino I, Zurro D, Salvatelli L (2012) Oxygen isotopic composition of limpet shells from the Beagle Channel: implications for seasonal studies in shell middens of Tierra del Fuego. *J Archaeol Sci* 39(6):1738–1748.
<https://doi.org/10.1016/j.jas.2012.01.012>

da Conceição Freitas M, Andrade C, Rocha F, Tassinari C, Munhá JM, Cruces A, Vidinha J, Marques da Silva C (2003) Lateglacial and Holocene environmental changes in Portuguese coastal lagoons 1: the sedimentological and geochemical records of the Santo André coastal area. *The Holocene* 13(3):433–446. <https://doi.org/10.1191/0959683603hl636rp>

Conyers, L., Bicho, N., Daniels, M., Elliot, K., Castro, G., Cascalheira, J., Gonçalves, C., n.d. Ground-penetrating radar mapping at the Mesolithic Muge Shell Mound, Portugal, in: Muge 150th. 150th Anniversary of the Discovery of the Mesolithic Shellmiddens

Cook PK, Languille M-A, Dufour E, Mocuta C, Tombret O, Fortuna F, Bertrand L (2015) Biogenic and diagenetic indicators in archaeological and modern otoliths: potential and limits of high definition synchrotron micro-XRF. *Chem. Geol* 414:1–15.
<https://doi.org/10.1016/j.chemgeo.2015.08.0170009-2541>

Costa MJ (1999) *O Estuário do Tejo*. Livros Cotovia, Viseu

Cunha E, Umbelino C (1995) Abordagem antropológica das comunidades mesolíticas dos concheiros do Sado. *O Arqueólogo Port Série IV*:161–179

Cunha E, Cardoso F, Umbelino C (2003) Inferences about Mesolithic lifestyle on the basis of anthropological data. In: Larsson L, Kindgren H, Knutsson K, Loeffler D, Akerlund A (eds) *The case of the Portuguese shell middens. Mesolithic on the move*, Oxford, pp 184–188

Davis Ba S, Brewer S, Stevenson AC, Guiot J (2003) The temperature of Europe during the Holocene reconstructed from pollen data. *Quat Sci Rev* 22(15-17):1701–1716. [https://doi.org/10.1016/S0277-3791\(03\)00173-2](https://doi.org/10.1016/S0277-3791(03)00173-2)

Detry, C., 2000. Estudo Arqueozoológico dos Concheiros de Muge. Relatório de estágio profissionalizante da Licenciatura em Biologia Aplicada aos Recursos Animais - Variante Terrestres. Lisboa

Detry, C., 2007. *Paleoecologia e Paleoeconomia do Baixo Tejo no Mesolítico Final: O contributo do estudo dos mamíferos dos concheiros de Muge*. Paleoeecologia e Paleoeconomia do Baixo Tejo no Mesolítico Final: O contributo do estudo dos mamíferos dos concheiros de Muge Cle. Historia Santiago. Universidade de Salamanca e Universidade Autónoma de Lisboa

- Detry C (2008) Vertebrates from Cabeço dos Morros: a Mesolithic shell midden near Salvaterra de Magos, in the lower Tagus valley, Portugal. *PRO* 6:51–70
- Dias R, Cascalheira J, Gonçalves C, Detry C, Bicho N (2012) Preliminary analysis of the spatial relationships between faunal and lithic remains on the Mesolithic Shelmidden of Cabeço da Amoreira (Muge, Portugal). In: Campar Almeida A, Bettencourt AMS, Moura D, Monteiro-Rodrigues S, Alves MIC (eds) *Mudanças Ambientais E Interação Humana Na Fachada Atlântica occidental/environmental change and human interaction in the western Atlantic Façade*. APEQ, Coimbra, pp 159–164
- Dias, R., Detry, C., Pereira, A., 2015. What's new? The animal remains from Cabeço da Amoreira from the 2008-2012 campaigns, in: Bicho, N., Detry, C., Price, D.T., Cunha, E. (Eds.), *Muge 150th. 150th Anniversary of the Discovery of the Mesolithic Shellmiddens*. Cambridge Scholars Publishing, pp. 105–118
- Dias R, Detry C, Bicho N (2016) Changes in the exploitation dynamics of small terrestrial vertebrates and fish during the Pleistocene-Holocene transition in the SW Iberian Peninsula: a review. *The Holocene* 26(6):964–984. <https://doi.org/10.1177/0959683615622547>
- Disspain M, Wallis LA, Gillanders BM (2011) Developing baseline data to understand environmental change: a geochemical study of archaeological otoliths from the Coorong, South Australia. *J Archaeol Sci* 38(8):1842–1857. <https://doi.org/10.1016/j.jas.2011.03.027>
- Disspain MCF, Ulm S, Gillanders BM (2015) Otoliths in archaeology: methods, applications and future prospects. *J Archaeol Sci Reports* 6:623–632. <https://doi.org/10.1016/j.jasrep.2015.05.012>
- Dufour E, Cappetta H, Denis A, Dauphin Y, Mariotti A (2000) La diagenese des otolithes par la comparaison des donnees microstructurales, mineralogiques et geochimiques; application aux fossiles du Pliocene du Sud-Est de la France. *Bull la Soc Geol Fr* 171(5):521–532. <https://doi.org/10.2113/171.5.521>
- Dupont C (2016) Could occupation duration be related to the diversity of faunal remains in Mesolithic shell middens along the European Atlantic seaboard? *Quat Int* 407:145–153. <https://doi.org/10.1016/j.quaint.2016.01.039>

Dupont C, Tresset A, Desse-Berset N, Gruet Y, Marchand G, Schulting R (2009) Harvesting the seashores in the late Mesolithic of northwestern Europe: a view from Brittany. *J World Prehistory* 22(2):93–111. <https://doi.org/10.1007/s10963-009-9017-3>

Figueiral I (1993) Cabeço de Porto Marinho: une approche paléoécologique. Premières résultats. In: Fumanal MP, Bernabeu J (eds) *Estudios Sobre Cuaternario*. Asociación Española para el estudio del Cuaternario, València, pp 167–172

Figueiral I, Carcaillet C (2005) A review of Late Pleistocene and Holocene biogeography of highland Mediterranean pines (*Pinus type sylvestris*) in Portugal, based on wood charcoal. *Quat Sci Rev* 24(23-24):2466–2476. <https://doi.org/10.1016/j.quascirev.2005.02.004>

Figueiral I, Terral J-F (2002) Late Quaternary refugia of Mediterranean taxa in the Portuguese Estremadura: charcoal based palaeovegetation and climatic reconstruction. *Quat Sci Rev* 21(4-6):549–558. [https://doi.org/10.1016/S0277-3791\(01\)00022-1](https://doi.org/10.1016/S0277-3791(01)00022-1)

Fletcher WJ (2005) *Holocene landscape history of southern Portugal*. University of Cambridge

Fletcher WJ, Sánchez Goñi MF, Allen JRM, Cheddadi R, Combourieu-Nebout N, Huntley B, Lawson I, Londeix L, Magri D, Margari V, Müller UC, Naughton F, Novenko E, Roucoux K, Tzedakis PC (2010) Millennial-scale variability during the last glacial in vegetation records from Europe. *Quat Sci Rev* 29(21-22):2839–2864. <https://doi.org/10.1016/j.quascirev.2009.11.015>

Foster LC, Andersson C, Høie H, Allison N, Finch AA, Johansen T (2008) Effects of micromilling on δ 18 O in biogenic aragonite. *Geochem Geophys Geosyst* 9:n/a–n/a. <https://doi.org/10.1029/2007GC001911>

Frigola J, Moreno A, Cacho I, Canals M, Sierro FJ, Flores JA, Grimalt JO, Hodell DA, Curtis JH (2007) Holocene climate variability in the western Mediterranean region from a deepwater sediment record. *Paleoceanography* 22(2). <https://doi.org/10.1029/2006PA001307>

Gabriel S (2007) A exploração dos recursos ictícos. In: Araújo AC (ed) *O Concheiro de Toledo No Contexto Do Mesolítico Inicial Do Litoral Da Estremadura*. Instituto Português de Arqueologia, Lisbon, pp 127–145

Gabriel S (2011) A exploração dos recursos ictícos. In: Araújo AC (ed) O Concheiro de Toledo No Contexto Do Mesolítico Inicial Do Litoral Da Estremadura, Trabalhos de Arqueologia, vol 51. IGESPAR, Lisboa, pp 127–143

Gabriel, S., 2015. La Ictiofauna del Holoceno Inicial y Medio de Portugal. Implicaciones tafonómicas, ecológicas y culturales. Universidad Autonoma de Madrid

Gabriel S, Prista N, Costa MJ (2012) Estimating meagre (*Argyrosomus regius*) size from otoliths and vertebrae. *J Archaeol Sci* 39(9):2859–2865. <https://doi.org/10.1016/j.jas.2012.04.046>

Gonçalves, C., 2009. Modelos preditivos da SIG na localização de sítios arqueológicos de cronologia mesolítica no Vale do Tejo. Universidade do Algarve

Griffiths MH, Hecht T (1995) Age and growth of South African dusky kob *Argyrosomus japonicus* (Scianidae) based on otoliths. *South African J Mar Sci* 16(1):119–128. <https://doi.org/10.2989/025776195784156548>

Gutiérrez-Zugasti I, Andersen SH, Araújo AC, Dupont C, Milner N, Monge-Soares AM (2011) Shell midden research in Atlantic Europe: state of the art, research problems and perspectives for the future. *Quat Int* 239(1-2):70–85. <https://doi.org/10.1016/j.quaint.2011.02.031>

Haws, J.A., 2003. An investigation of Late Upper Paleolithic and Epipaleolithic hunter-gatherer subsistence and settlement patterns in Central Portugal. University of Wisconsin-Madison

Haws J, Valente MJ (2006) Animal carcass utilization during the late upper Paleolithic occupation of Lapa do Suão (Portugal). In: Haws J, Brugal J-P, Hockett B (eds) *Paleolithic zooarchaeology in practice*. S1954. BAR International Series. Archaeopress, Oxford, pp 29–37

Higham TF, Horn P (2000) Seasonal dating using fish otoliths: results from the Shag River Mouth Site, New Zealand. *J Archaeol Sci* 27(5):439–448. <https://doi.org/10.1006/jasc.1999.0473>

Hoie H, Folkvord A (2006) Estimating the timing of growth rings in Atlantic cod otoliths using stable oxygen isotopes. *J Fish Biol* 68(3):826–837. <https://doi.org/10.1111/j.0022-1112.2006.00957.x>

- Hufthammer AK, Høie H, Folkvord A, Geffen AJ, Andersson C, Ninnemann US (2010) Seasonality of human site occupation based on stable oxygen isotope ratios of cod otoliths. *J Archaeol Sci* 37(1):78–83.
<https://doi.org/10.1016/j.jas.2009.09.001>
- Iacumin P, Bianucci G, Longinelli A (1992) Oxygen and carbon isotopic composition of fish otoliths. *Mar Biol* 113(4):537–542.
<https://doi.org/10.1007/BF00349696>
- Jesus, L., Marreiros, J., Cascalheira, J., Gibaja, J., Pereira, T., Bicho, N., (n.d). Occupation, functionality and culture. Preliminary results from microliths technology and use-wear analysis of Cabeço da Amoreira (Muge, Portugal), in: The Eighth International Conference on the Mesolithic in Europe Will Be Held in Santander from 13th to 17th September 2010, Cantabrian International Institute for Prehistoric Research. Santander
- Jones TL, Kennett DJ, Kennett JP, Coddling BF (2008) Seasonal stability in Late Holocene shellfish harvesting on the central California coast. *J Archaeol Sci* 35(8):2286–2294. <https://doi.org/10.1016/j.jas.2008.03.002>
- Julião RP, Pereira da Silva C, Loução J, Tenedório JA, Lôbo MS, Roxo MJ, Soares N, Salvador R (1998) Atlas de Lisboa e Vale do Tejo. Universidade Nova de Lisboa, Lisboa
- Kalish JM (1991) ^{13}C and ^{18}O isotopic disequilibria in fish otoliths: metabolic and kinetic effects. *Mar Ecol Prog Ser* 75:191–203.
<https://doi.org/10.3354/meps075191>
- Kennett DJ, Voorhies B (1996) Oxygen isotopic analysis of archaeological shells to detect seasonal use of wetlands on the southern Pacific coast of Mexico. *J Archaeol Sci* 23(5):689–704.
<https://doi.org/10.1006/jasc.1996.0065>
- van der Knaap WO, van Leeuwen JFN (1997) Late Glacial and early Holocene vegetation succession, altitudinal vegetation zonation, and climatic change in the Serra da Estrela, Portugal. Review of Palaeobotany and Palynology 97(3-4):239–285. [https://doi.org/10.1016/S0034-6667\(97\)00008-0](https://doi.org/10.1016/S0034-6667(97)00008-0)
- Lentacker A (1986a) Preliminary results of the fauna of Cabço de Amoreira and Cabeço de Arruda (Muge, Portugal). *Trab Antropol e Etnol* 26:9–26

Lentacker A (1986b) Preliminary results of the fauna of Cabeço da Amoreira and Cabeço da Arruda (Muge, Portugal). *Trab Antropol e Etnol.* 26:9–26

Lentacker A (1994) Fish remains from Portugal: preliminary analysis of the Mesolithic shell-midden sites of Cabeço da Amoreira and Cabeço da Arruda. *Ann du Musée R l'Afrique Cent Sci Zool* 274:263–271

Mannino MA, Spiro BF, Thomas KD (2003) Sampling shells for seasonality: oxygen isotope analysis on shell carbonates of the inter-tidal gastropod *Monodonta lineata* (da Costa) from populations across its modern range and from a Mesolithic site in southern Britain. *J Archaeol Sci* 30(6):667–679. [https://doi.org/10.1016/S0305-4403\(02\)00238-8](https://doi.org/10.1016/S0305-4403(02)00238-8)

Mannino MA, Thomas KD, Leng MJ, Piperno M, Tusa S, Tagliacozzo A (2007) Marine resources in the Mesolithic and Neolithic at the Grotta Dell'Uzzo (Sicily): evidence from isotope analyses of marine shells*. *Archaeometry* 49(1):117–133. <https://doi.org/10.1111/j.1475-4754.2007.00291.x>

Marreiros, J., Gibaja, J., Paixão, E., Pereira, T., Cascalheira, J., BICHO, N., 2015. New evidences for human settlement organization from the Mesolithic site of Cabeço da Amoreira (Muge): preliminary lithic use-wear analysis, in: Bicho, N., Detry, C., Cunha, E., Price, D.T. (Eds.), *Proceedings of the Muge 150th anniversary of the discovery of the Mesolithic Shellmiddens*. Cambridge Scholars Publishing, Cambridge, pp. 133–144

Marreiros, J., Jesus, L., Cascalheira, J., Pereira, T., Gibaja, J., Bicho, N., n.d. “Shell we move?” New technological approach to Mesolithic settlement patterns at Muge (Portuguese Estremadura), in: *The Eighth International Conference on the Mesolithic in Europe will be held in Santander from 13th to 17th September 2010*, Cantabrian International Institute for Prehistoric Research. Santander

McDermott F, Matthey D, Hawkesworth C (2001) Centennial-scale Holocene climate variability revealed by a high-resolution speleothem delta 18O record from SW Ireland. *Science* 294(80):1328–1331. <https://doi.org/10.1126/science.1063678>

McManus JF, Oppo DO, Cullen JL (1999) A 0.5-million-year record of millennial-scale climate variability in the North Atlantic. *Science* 293(80):971–975

van der Merwe NJ, Williamson RF, Pfeiffer S, Thomas SC, Allegretto KO (2003) The Moatfield ossuary: isotopic dietary analysis of an Iroquoian community, using dental tissue. *J Anthropol Archaeol* 22(3):245–261. [https://doi.org/10.1016/S0278-4165\(03\)00038-2](https://doi.org/10.1016/S0278-4165(03)00038-2)

Monge Soares, A.M., 2005. Variabilidade do “upwelling” costeiro durante o holocénico nas margens atlânticas ocidental e meridional da Península Ibérica. Universidade do Algarve

Monge Soares AM (2006) Coastal upwelling and radiocarbon—evidence for temporal fluctuations in ocean reservoir effect off Portugal during the Holocene. *Radiocarbon* 48(01):45–60. <https://doi.org/10.1017/S0033822200035384>

Monks GG (1981) Seasonality studies. *Adv Archaeol method theory* 4:177–240

Monteiro, P., 2011. Woodland exploitation during the Mesolithic: anthracological study of new samples from Cabeço da Amoreira (Muge, Portugal). North. Universidad del País Vasco

Monteiro P (2012) Woodland exploitation during the Mesolithic: anthracological study of new samples from Cabeço da Amoreira (Muge, Portugal). *Leioa* 2:38–47

Monteiro, P., Zapata, L., n.d. The Midden is on fire! Charcoal analysis from Cabeço da Amoreira (Muge Shellmiddens), in: Muge 150th. 150th Anniversary of the Discovery of the Mesolithic Shellmiddens

Moreno García M (2010) Exploração de recursos faunísticos de origem terrestre. In: Araújo AC (ed) *O Concheiro de Toledo No Contexto Do Mesolítico Do Litoral Da Estremadura*, vol 53. *Trabalhos de Arqueologia*, Lisbon, pp 99–125

Moreno-García M (2011) Exploração dos recursos faunísticos de origem terrestre. In: Araújo AC (ed) *O Concheiro de Toledo No Contexto Do Mesolítico Do Litoral Da Estremadura*, *Trabalhos de Arqueologia*, vol 53. Ministério da Cultura. IGESPAR, Lisboa, pp 99–126

Neeley MP, Clark GA (1990) Measuring social complexity in the European Mesolithic. In: Vermeersch PM, Van Peer P (eds) *Contributions to the Mesolithic in Europe*. Leuven University Press, Leuven, pp 127–137

- Park M-H (1998) Abrupt climatic changes induced by ice-rafting events in the eastern North Atlantic during the late Quaternary: stable isotope and X-ray mineralogical analyses. *Geosci J* 2(2):59–67.
<https://doi.org/10.1007/BF02910484>
- Penaud A, Eynaud F, Turon JL, Blamart D, Rossignol L, Marret F, Lopez-Martinez C, Grimalt JO, Malaizé B, Charlier K (2010) Contrasting paleoceanographic conditions off Morocco during Heinrich events (1 and 2) and the Last Glacial Maximum. *Quat Sci Rev* 29(15-16):1923–1939.
<https://doi.org/10.1016/j.quascirev.2010.04.011>
- Pollard, D.A., Yokes, B., Kara, M., Bizsel, K., Quignard, J.P., 2015. *Argyrosomus regius* [WWW document]. IUCN Red List Threat. Species 2015. URL doi: <https://doi.org/10.2305/IUCN.UK.2015-4.RLTS.T198706A49227019.en> (accessed 4.14.16)
- Póvoas, L., 2001. Contribuição do estudo das associações de roedores para o conhecimento de variações climáticas durante o Quaternário em Portugal, in: *Actas Da V Reunião Do Quaternário Ibérico/ I Congresso Do Quaternário de Países de Línguas Ibéricas*
- Prista, N.M.G.G., 2013. *Argyrosomus regius* (Asso, 1801) fishery and ecology in Portuguese waters, with reference to its relationships to other European and African populations Nuno Miguel Guerra Geoffroy Prista
- Prista, N., Costa, J.L., Costa, M.J., Jones, C., 2009. Age determination in meagre *Argyrosomus regius*. *Relat Cient Téc Inst Invest Pescas Mar* 49, pp. 54
- Quitmyer IR, Jones DS, Arnold WS (1997) The sclerochronology of hard clams, *Mercenaria* spp., from the South-Eastern U.S.A.: a method of elucidating the zooarchaeological records of seasonal resource procurement and seasonality in prehistoric shell middens. *J Archaeol Sci* 24(9):825–840.
<https://doi.org/10.1006/jasc.1996.0163>
- Radtke RL, Lenz P, Showers W, Moksness E (1996) Environmental information stored in otoliths: insights from stable isotopes. *Mar Biol* 127(1):161–170. <https://doi.org/10.1007/BF00993656>
- Ramos C, Reis E (2001) As cheias no Sul de Portugal em diferentes tipos de bacias hidrográficas. *Finisterra* 71:61–82

Rasmussen SO, Andersen KK, Svensson AM, Steffensen JP, Vinther BM, Clausen HB, Siggaard-Andersen M-L, Johnsen SJ, Larsen LB, Dahl-Jensen D, Bigler M, Röthlisberger R, Fischer H, Goto-Azuma K, Hansson ME, Ruth U (2006) A new Greenland ice core chronology for the last glacial termination. *J Geophys Res* 111(D6):D06102.
<https://doi.org/10.1029/2005JD006079>

Richards MP, Hedges REM (1999) Stable isotope evidence for similarities in the types of marine foods used by Late Mesolithic humans at sites along the Atlantic Coast of Europe. *J Archaeol Sci* 26(6):717–722.
<https://doi.org/10.1006/jasc.1998.0387>

Robson H, Andersen S, Craig O, Fischer A, Glykou A, Hartz S, Lübke H, Schmölcke U, Heron C (2012) Carbon and nitrogen isotope signals in eel bone collagen from Mesolithic and Neolithic sites in northern Europe. *J Archaeol Sci* 39(7):2003–2011. <https://doi.org/10.1016/j.jas.2012.01.033>

Robson, H.K., Andersen, S.H., Clarke, L., Craig, O.E., Kurt, J., Jones, A.K.G., Karsten, P., Milner, N., Price, T.D., Ritchie, K., Heron, C., Gron, K.J., G Jones, A.K., Karsten, P., Milner, N., Douglas Price, T., Ritchie, K., Zabilska-Kunek, M., Heron, C., 2015. Carbon and nitrogen stable isotope values in freshwater, brackish and marine fish bone collagen from Mesolithic and Neolithic sites in central and northern Europe. *Environ Archaeol* 0. doi: <https://doi.org/10.1179/1749631415Y.0000000014> , Carbon and nitrogen stable isotope values in freshwater, brackish and marine fish bone collagen from Mesolithic and Neolithic sites in central and northern Europe, 21, 2, 105, 118

Robson HK, Andersen SH, Clarke L, Craig OE, Gron KJ, Jones AKG, Karsten P, Milner N, Price TD, Ritchie K, Zabilska-Kunek M, Heron C (2016) Carbon and nitrogen stable isotope values in freshwater, brackish and marine fish bone collagen from Mesolithic and Neolithic sites in central and northern Europe. *Environ Archaeol* 21(2):105–118.
<https://doi.org/10.1179/1749631415Y.0000000014>

Rodrigues, T., Grimalt, J.O., Abrantes, F.G., Flores, J.A., Lebreiro, S.M., 2009. Holocene interdependences of changes in sea surface temperature, productivity, and fluvial inputs in the Iberian continental shelf (Tagus mud patch). *Geochemistry, Geophys. Geosystems* 10, n/a-n/a. doi: <https://doi.org/10.1029/2008GC002367>

Rolão, J., 1999. Del Würm Final al Holocénico en el Bajo Valle del Tajo. Complejo arqueológico mesolítico de Muge. Universidade de Salamanca

Roucoux KH, Shackleton NJ, de Abreu L, Schönfeld J, Tzedakis PC (2001) Combined marine proxy and pollen analyses reveal rapid Iberian vegetation response to North Atlantic millennial-scale climate oscillations. *Quat Res* 56(01):128–132. <https://doi.org/10.1006/qres.2001.2218>

Salgueiro E, Voelker AHL, de Abreu L, Abrantes F, Meggers H, Wefer G (2010) Temperature and productivity changes off the western Iberian margin during the last 150 ky. *Quat Sci Rev* 29(5-6):680–695. <https://doi.org/10.1016/j.quascirev.2009.11.013>

Santos, C.T.N. dos, 2010. Reconstrução das condições paleoambientais e paleoclimáticas no estuário do Tejo durante o Holocénico (~12000 anos). Universidade do Porto

Santos L, Fernanda Sánchez Goñi M (2003) Late glacial and Holocene environmental changes in Portuguese coastal lagoons 3: vegetation history of the Santo Andre' coastal area. *The Holocene* 13(3):459–464. <https://doi.org/10.1191/0959683603hl638rp>

Schönfeld J, Zahn R (2000) Late glacial to Holocene history of the Mediterranean outflow. Evidence from benthic foraminiferal assemblages and stable isotopes at the Portuguese margin. *Palaeogeogr Palaeoclimatol Palaeoecol* 159(1-2):85–111. [https://doi.org/10.1016/S0031-0182\(00\)00035-3](https://doi.org/10.1016/S0031-0182(00)00035-3)

Schriek, T. van der, 2004. Holocene environmental change and the alluvial geoarchaeology of Mesolithic settlement-subsistence in the Muge and Magos Valleys, lower Tagus basin, Portugal. University of Newcastle upon Tyne

van der Schriek T, Passmore DG, Franco Mugica F, Stevenson AC, Boomer I, Rolão J (2008) Holocene palaeoecology and floodplain evolution of the Muge tributary, Lower Tagus Basin. Portugal *Quat Int* 189(1):135–151. <https://doi.org/10.1016/j.quaint.2007.09.007>

Scourse J, Richardson C, Forsythe G, Harris I, Heinemeier J, Fraser N, Briffa K, Jones P (2006) First cross-matched floating chronology from the marine fossil record: data from growth lines of the long-lived bivalve mollusc *Arctica islandica*. *The Holocene* 16(7):967–974. <https://doi.org/10.1177/0959683606hl987rp>

- Shackleton NJ (1973) Oxygen isotope analysis as a means of determining season of occupation of prehistoric midden sites. *Archaeometry* 15(1):133–141. <https://doi.org/10.1111/j.1475-4754.1973.tb00082.x>
- Spikins P (2009) Mesolithic Europe: glimpses of another world. In: Spikins P (ed) Bailey, G. Cambridge University Press, Mesolithic Europe, pp 1–17
- Surge D, Walker KJ (2005) Oxygen isotope composition of modern and archaeological otoliths from the estuarine hardhead catfish (*Ariopsis felis*) and their potential to record low-latitude climate change. *Palaeogeogr Palaeoclimatol Palaeoecol* 228(1-2):179–191. <https://doi.org/10.1016/j.palaeo.2005.03.051>
- Szpak P (2011) Fish bone chemistry and ultrastructure: implications for taphonomy and stable isotope analysis. *J Archaeol Sci* 38(12):3358–3372. <https://doi.org/10.1016/j.jas.2011.07.022>
- Thorrold SR, Campana SE, Jones CM, Swart PK (1997) Factors determining $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ fractionation in aragonitic otoliths of marine fish. *Geochim Cosmochim Acta* 61(14):2909–2919. [https://doi.org/10.1016/S0016-7037\(97\)00141-5](https://doi.org/10.1016/S0016-7037(97)00141-5)
- Turon J (2003) Land–sea correlations for the last glaciation inferred from a pollen and dinocyst record from the Portuguese margin. *Quat Res* 59(01):88–96. [https://doi.org/10.1016/S0033-5894\(02\)00018-2](https://doi.org/10.1016/S0033-5894(02)00018-2)
- Umbelino, C., 2006. Outros Sabores do Passado. As análises de oligoelementos e de isótopos estáveis na reconstituição da dieta das comunidades humanas do Mesolítico Final e do Neolítico Final / Calcolítico do território português. Universidade de Coimbra
- Van Der Schriek T, Passmore DG, Anthony C, Rolão J (2007) The palaeogeography of Mesolithic settlement-subsistence and shell midden formation in the Muge valley, Lower Tagus Basin, Portugal. *The Holocene* 17:369–385
- Trueman CN, Chung M-T, Shores D (2016) Ecogeochemistry potential in deep time biodiversity illustrated using a modern deep-water case study. *Philos Trans R Soc B Biol Sci* 371:20150223. <https://doi.org/10.1098/rstb.2015.0223>

Van Leeuwaarden W, Queiróz PF (2003) Estudos de Arqueobotânica no sítio da Ponta da Vigia. *Rev Port Arqueol* 6:79–81

Van Neer W, Augustynen S, Linkowski T (1993) Daily growth increments on fish otoliths as seasonality indicators on archaeological sites: the Tilapia from late Palaeolithic Makhadma in Egypt. *Int J Osteoarchaeol* 3(4):241–248. <https://doi.org/10.1002/oa.1390030403>

Vis G-J, Bohncke SJP, Schneider H, Kasse C, Coenraads-Nederveen S, Zuurbier K, Rozema J (2010) Holocene flooding history of the Lower Tagus Valley (Portugal). *J Quat Sci* 25(8):1222–1238. <https://doi.org/10.1002/jqs.1401>

Voelker A, Lebreiro S, Schonfeld J, Cacho I, Erlenkeuser H, Abrantes F (2006) Mediterranean outflow strengthening during northern hemisphere coolings: a salt source for the glacial Atlantic? *Earth planet Sci Lett* 245(1–2):39–55. <https://doi.org/10.1016/j.epsl.2006.03.014>

Wang T, Surge D, Walker KJ (2011) Isotopic evidence for climate change during the Vandal Minimum from *Ariopsis felis* otoliths and *Mercenaria campechiensis* shells, southwest Florida, USA. *The Holocene* 21(7):1081–1091. <https://doi.org/10.1177/0959683611400458>

Wang T, Surge D, Walker KJ (2013) Seasonal climate change across the Roman warm period/vandal minimum transition using isotope sclerochronology in archaeological shells and otoliths, southwest Florida, USA *Quat Int* 308–309:230–241. <https://doi.org/10.1016/j.quaint.2012.11.013>

Wefer G, Berger WH (1991) Isotope paleontology: growth and composition of extant calcareous species. *Mar Geol* 100(1–4):207–248. [https://doi.org/10.1016/0025-3227\(91\)90234-U](https://doi.org/10.1016/0025-3227(91)90234-U)

Wheeler A, Jones AKG (2009) *Fishes*. Cambridge University Press, Cambridge

Wurster CM, Patterson WP (2001) Late Holocene climate change for the eastern interior United States: evidence from high-resolution $\delta^{18}\text{O}$ values of sagittal otoliths. *Palaeogeogr Palaeoclimatol Palaeoecol* 170(1–2):81–100. [https://doi.org/10.1016/S0031-0182\(01\)00229-2](https://doi.org/10.1016/S0031-0182(01)00229-2)

Wurster CM, Patterson WP (2003) Metabolic rate of late Holocene freshwater fish: evidence from $\delta^{13}\text{C}$ values of otoliths. *Paleobiology* 29(4):492–505.

[https://doi.org/10.1666/0094-8373\(2003\)029<0492:MROLHF>2.0.CO;2](https://doi.org/10.1666/0094-8373(2003)029<0492:MROLHF>2.0.CO;2)

Zahn R, Schönfeld J, Kudrass H-R, Park M-H, Erlenkeuser H, Grootes P (1997) Thermohaline instability in the North Atlantic during meltwater events: stable isotope and ice-rafted detritus records from Core SO75-26KL, Portuguese Margin. *Paleoceanography* 12(5):696–710.
<https://doi.org/10.1029/97PA00581>

Zambujo G, Lourenço S (2002) Duas novas datações absolutas para a Ponta da Vigia. *Rev Port Arqueol* 6:69–78

Zilhão J, Marks A, Ferring R, AI E (1996) The Upper Paleolithic of the Rio Maior basin (Portugal). Preliminary results of a 1987–1993 Portuguese-American research project. *Trab Antropol e Etnol* 36:69–82