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Reprint of "Shell oxygen isotope values and sclerochronology of the limpet *Patella vulgata* Linnaeus 1758 from northern Iberia: Implications for the reconstruction of past seawater temperatures"☆

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ABSTRACT

Understanding environmental conditions faced by hunter-fisher-gatherers during the Pleistocene and Holocene, and interpretation of subsistence strategies, social organisation and settlement patterns, are key topics for the study of past human societies. In this respect, oxygen isotope values ($\delta^{18}O$) of mollusc shell calcium carbonate can provide important information on palaeoclimate and the seasonality of shell collection at archaeological sites. In this paper, we tested *P. vulgata* shells from northern Iberia as a paleoclimate archive through the study of shell oxygen isotope values and sclerochronology of modern samples. Results showed that limpets formed their shells close to isotopic equilibrium, with an average offset between measured and predicted values of 0.36‰. This offset is significantly reduced with respect to those reported in previous studies, probably due to the use of highly resolved data on the isotopic composition of the water when calculating predicted values. Despite large intra-specific variability, shell growth patterns of *P. vulgata* revealed a common pattern of higher growth in spring and a growth cessation/slowdown in summer and winter. The seasonal growth cessation/slowdown did not exceed three months. Therefore, a correct interpretation of the season of shell collection is still possible. Reconstructed seawater temperature exhibited a high correlation with instrumental temperature ($R^2 = 0.68$ to 0.93; $p < 0.0001$). Despite periods of growth cessation/slowdown, mean seawater temperatures and annual ranges were reconstructed accurately. As demonstrated here, seawater temperature can be reconstructed with a maximum uncertainty of ± 2.7 °C. Therefore, our study shows that oxygen isotope values from *P. vulgata* can be used for the reconstruction of paleoclimate and the season of shell collection.

1. Introduction

Marine molluscs are usually found in archaeological sites worldwide (Colonese et al., 2011; Erlandson, 2001; Gutiérrez-Zugasti et al., 2011). Ancient shells can provide a wide range of information on past subsistence strategies (e.g. Ainis et al., 2014; Cuenca-Solana, 2015; Manne and Bicho, 2011; Vanhaeren and d'Errico, 2006), but they also serve as palaeoclimate archives (Andrus, 2011; Schöne et al., 2004; Surge et al., 2003). Many molluscs grow their shells in isotopic equilibrium with the surrounding environment. This means that during shell formation chemical signatures from the environment in which the shells were living are incorporated into the carbonate (Dettman et al., 1999). The oxygen isotope value ($\delta^{18}O_{shell}$) in shell carbonate is mainly a function of both the temperature and the oxygen isotope composition of the ambient water experienced by the mollusc during shell formation (Wanamaker et al., 2006). Therefore, oxygen isotope signatures recorded in ancient shells can be potentially used for reconstruction of past seawater temperatures, but also for determination of subsistence strategies and settlement patterns of past populations through the study of season of shell collection (Burchell et al., 2013; Colonese et al., 2009; Culleton et al., 2009; Mannino et al., 2003).

However, before oxygen isotope based techniques are applied to archaeological material, it is necessary to understand how reliably modern representatives of the respective species record their environment by means of $\delta^{18}O_{shell}$ (see for example Hallmann et al., 2009;

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Prendergast et al., 2013). A range of kinetic factors (usually known as "vital effects") can disrupt isotopic equilibrium. For example, a systematic offset from isotopic equilibrium has been found in shells of various *Patella* species across the eastern Atlantic and the Mediterranean (e.g. Fenger et al., 2007; Ferguson et al., 2011). This offset is different between species, but also between localities, suggesting that physiological responses of limpets might be environmentally driven. Similarly, investigations on the topshell *Phorcus turbinatus* have shown that the same species can respond differently in different locations, displaying variable offsets (Colonese et al., 2009; Mannino et al., 2008; Prendergast et al., 2013, 2016). Therefore, it is important to test isotopic equilibrium on shells from the same region where archaeological shells are going to be used for the reconstruction of past seawater temperatures. Apart from vital effects, interpretation of shell oxygen isotope values in terms of seawater temperatures can be biased by environmental factors, such as the isotopic composition of the seawater ($\delta^{18}O_{water}$). Variations in the $\delta^{18}O_{water}$ of the oceans are influenced by global (e.g. ice melting) and local processes (e.g. precipitation/evaporation balance, freshwater input, advecting or upwelling). At a local scale, surface water salinity and $\delta^{18}O_{water}$ are highly correlated, as they increase with evaporation and decrease with precipitation (Ravelo and Hillaire-Marcel, 2007). Given that $\delta^{18}O_{shell}$ is a function of both seawater temperature and $\delta^{18}O_{water}$, it is important to know the contribution of $\delta^{18}O_{water}$ to $\delta^{18}O_{shell}$ through calibration of modern shells and comparison with instrumental data. Finally, information on shell growth patterns (timing and rate of seasonal shell formation) is also crucial for a correct interpretation of isotopic data. Molluscs usually grow more slowly or even stop growing at different times of the year and for various different reasons (e.g. extreme temperatures, storms, spawning, etc.) (Schöne, 2008). During growth cessation environmental signals are not recorded by the shell, and therefore actual seawater temperatures can be under- and/or overestimated.

Northern Iberia is a key region for the study of long-term changes in hunter-fisher-gatherer societies. Numerous Upper Palaeolithic and Mesolithic sites have been recorded in the region, providing one of the richest archaeological records in the world for the study of the Pleistocene-Holocene transition. Shells of different species, such as *Phorcus lineatus* (da Costa, 1778), *Patella vulgata* Linnaeus, 1758 and *Patella depressa* Pennant, 1777 have been abundantly recorded at those archaeological sites. Among them, the limpet *P. vulgata* shows great potential for the study of long-term palaeoclimate sequences in this region, as this species is found in archaeological sites continuously from the Late Pleistocene to the Holocene. The first studies on shell oxygen isotopes from *P. vulgata* produced irregular patterns of environmental variations, probably due to sampling with coarse resolution (Craighead, 1995; Deith and Shackleton, 1986). Recently, high-resolution studies using modern and archaeological *P. vulgata* shells from Atlantic locations have confirmed the utility of this species for reconstruction of seawater temperatures and determination of growth patterns (Ambrose et al., 2015; Fenger et al., 2007; Ferguson et al., 2011; Surge and Barrett, 2012; Wang et al., 2012). However, only Fenger et al. (2007) conducted a calibration on this species, using modern shells from northern England. Information derived from this study was used for interpretation of oxygen isotope records from shells recovered in archaeological sites from the United Kingdom (Surge and Barrett, 2012; Wang et al., 2012). Later investigations by Surge et al. (2013), including modern shells from northern Iberia, produced oxygen isotope records following the same seasonal variations as seawater temperatures, but this study was focused on growth patterns rather than on palaeoenvironmental reconstruction. Therefore, despite the existence of previous isotopic studies in the region using modern specimens, a proper calibration of the $\delta^{18}O_{shell}$ as a palaeotemperature proxy has not yet been performed for this species in northern Iberia.

In this paper, we test the ability of *P. vulgata* shells from northern Spain as a palaeoclimate archive through the study of oxygen isotope values from modern samples. This study includes a tighter control of variables than in previous research (Fenger et al., 2007; Surge et al., 2013) by including a more accurate seawater monitoring, different sampling approaches and a detailed sclerochronological analysis. Results are used to discuss isotopic equilibrium, growth patterns, and reconstruction of seawater temperatures. We also discuss the potential and limits of the method and its implications for palaeoclimate and archaeological studies. Calibration of $\delta^{18}O_{shell}$ from *P. vulgata* as a proxy for determination of seawater temperatures in northern Iberia is crucial to understand environmental conditions faced by hunter-fisher-gatherers during the Pleistocene and the Holocene, and also for reconstruction of subsistence strategies and settlement patterns.

2. Study area and environmental setting

The study area is located in the north of the Iberian Peninsula, known as the Cantabrian Coast (Fig. 1). The climate is oceanic, humid, and temperate, with mild winters and summers. This is partly determined by geographical elements such as the North Atlantic Current, which cause the temperature to be higher than expected for this latitude (ca. 43°N). The mean annual atmospheric temperature is ~15–16 °C. January is the coldest month with an average temperature of 9–10 °C, and August the warmest month with 20–22 °C. The mean annual rainfall exceeds 1200 mm and shows a marked seasonality, with the wetter conditions in spring and autumn and the driest period coinciding with summer months (Source: AEMET, Agencia Estatal de Meteorología, http://www.aemet.es). The higher rainfall is a result of the Föhn effect because the mountains prevent the clouds from crossing inland to the Meseta in north-central Spain (Rasilla, 1999).

The Cantabrian Sea (southern Bay of Biscay) represents a boundary between subtropical and boreal conditions in the Eastern Atlantic. The area is dominated by semidiurnal tidal cycles (two high tides and two low tides every lunar day). Sea surface temperatures follow a seasonal warming and cooling pattern, ranging from ca. 22 °C to ca. 12 °C in the central part of the region (i.e. Santander, data from the Instituto Español de Oceanografía, IEO). Hydrographic conditions throughout the year follow a regular pattern characterised by winter mixing and summer stratification. Wind-induced upwelling events, which are characterised by low temperatures, high salinity, and nutrient concentrations, have been observed to occur mainly in summer (Álvarez et al., 2011; Lavín et al., 1998). The water related to these upwelling events in the region is generally Eastern North Atlantic Central Water (ENACW), which is a cold and salty water mass. However, some authors have also detected winter upwelling events associated with the Iberian Poleward Current (Gil et al., 2002) and with shelf bottom seawater (see Álvarez et al., 2011 and references therein).

3. Biology and ecology of *P. vulgata*

The limpet *P. vulgata* Linnaeus, 1758 inhabits the intertidal rocky shore from northern Norway to southern Portugal (Poppe and Goto, 1991). This species is adapted to cold water conditions and it is able to survive a wide range of atmospheric temperatures (from −9 °C to 43 °C) (Crisp, 1965; Branch, 1981). However, according to its geographical distribution, ideal conditions for *P. vulgata* development comprise seawater temperatures from ca. 8 °C to 19 °C and sea surface salinity from 20 to 35 psu (Fretter and Graham, 1976). Recent studies showed that thermal stress levels in *P. vulgata* are not primarily related to elevated air temperatures, but directly linked to elevated water temperature, showing an upper threshold of 23 °C (Seabra et al., 2016).

Growth rates on *P. vulgata* vary greatly, ranging from ~1.5 mm/year (Blackmore, 1969) to 4.4 mm/year (Jenkins and Hartnoll, 2001) for individuals sized between 25 and 35 mm. The longevity of this animal is highly dependent on the environmental conditions and has been reported to be up to ca. 16 years (Fischer-Piette, 1941). By comparison, a recent oxygen isotope study of specimens from northern England reconstructed a lifespan of up to ca. 8 years (Fenger et al., 2007). Studies