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## Shellfish Exploitation in the Western Canary Islands Over the Last Two Millennia

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### ABSTRACT

The residents of the Canary Archipelago consumed limpets since the arrival of humans ~2500 yrs. ago, and these harvested gastropods were deposited in large coastal shell middens. This work preliminarily explores shell margin oxygen isotope composition ( $\delta^{18}\text{O}$ ) and body size of the black limpet (*Patella candei* d'Orbigny, 1840) from archaeological sites in the Canary Islands to assess possible seasonal variability and intensity of shellfish collection throughout the late Holocene. The shell margin  $\delta^{18}\text{O}$  values of 100 shells (radiocarbon dated between ~500 and ~1800 cal. yr BP) were analysed to estimate sea surface temperature (SST) at time of death. Paleotemperature estimates suggest shellfish harvesting was not year-round, and was avoided in the cooler months (when SST < 20°C). This pattern differs from most higher latitude Mesolithic and Neolithic human groups, which gathered shellfish year-round, targeting winter more heavily. Preliminary body-size measurements suggest shell sizes have experienced a decline from aboriginal times to the present, which possibly resulted from increasing anthropogenic pressures. During aboriginal inhabitation, maximum adult shell size remained stable, suggesting that present-day harvesting practices are more intense than harvesting from aboriginal human groups. This intensive collection has likely diminished the average adult size of limpet populations in the islands by ~27%.

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## Introduction

Identifying the season of shellfish collection in archaeological deposits has been the focus of extensive research over the past 30 years to better understand how ancient humans interacted with their dynamic environment (Kennett and Voorhies 1996; Hallmann et al. 2009, 2013; Burchell et al. 2013; Kyriacou et al. 2015; Thomas 2015). Moreover, archaeological mollusc size has been used as a proxy for intensity of harvesting practices and to assess ecological response to resource exploitation by humans (Milner, Barrett, and Welsh 2007; Genner et al. 2010; Klein and Steele 2013). Together, understanding the intensity and seasonality of shellfish exploitation helps to constrain the impacts and responses of ancient humans and their environments throughout human history.

Early studies on the season of shellfish collection have used growth lines only – which are produced both annually and seasonally – to identify the season of collection by differentiating between growth lines that may have formed during warm or cold periods (Coutts 1970; Claassen 1983; Milner 2001). This method, however, is prone to error because growth lines can be produced by non-temperature stressors such as changes in salinity, turbidity, or even the stress

of spawning (Burchell et al. 2013). Recent advances in isotope sclerochronology, the study of the geochemical and physical information stored within the accretionary hard parts of organisms (Buddemeier, Maragos, and Knutson 1974; Andrus 2011; Surge and Schöne 2015), have provided higher resolution and accuracy in estimating season of collection through the development of oxygen isotope profiles throughout the lifespan of molluscs (Mannino and Thomas 2001; Mannino, Spiro, and Thomas 2003; Fenger et al. 2007; Mannino et al. 2007; Mannino and Leng 2008; Colonese et al. 2009; Hallmann et al. 2009, 2013; Andrus 2011; Wang, Surge, and Mithen 2012; Burchell et al. 2013; Surge et al. 2013; Wang, Surge, and Walker 2013). The shell margin, which represents the last growth episode of a shell, closest to organisms' death, contains an isotopic 'snapshot' of the sea surface temperature (SST) closest to the time of death. This approach can inform if shells were collected throughout the year or were preferentially collected during specific months or seasons. Many recent studies on the season of shellfish collection analyse at least 3–5 samples collected at ~2–3 mm intervals from the growth margin towards the apex (Jew et al. 2013, 2014). This method of isotopic analysis provides greater clarity into warming or

cooling trends, allowing for a relatively accurate characterisation of the season of shellfish harvest. While shell margin isotopic data cannot be used to determine the exact season of harvest (e.g. spring and fall seasons are difficult to discriminate), it does provide a cost-effective, useful dataset that can be used to preliminarily assess if shellfish were collected year-round or not (Parker et al. 2017). This determination can then form the basis for ongoing, high-resolution isotope sclerochronological study.

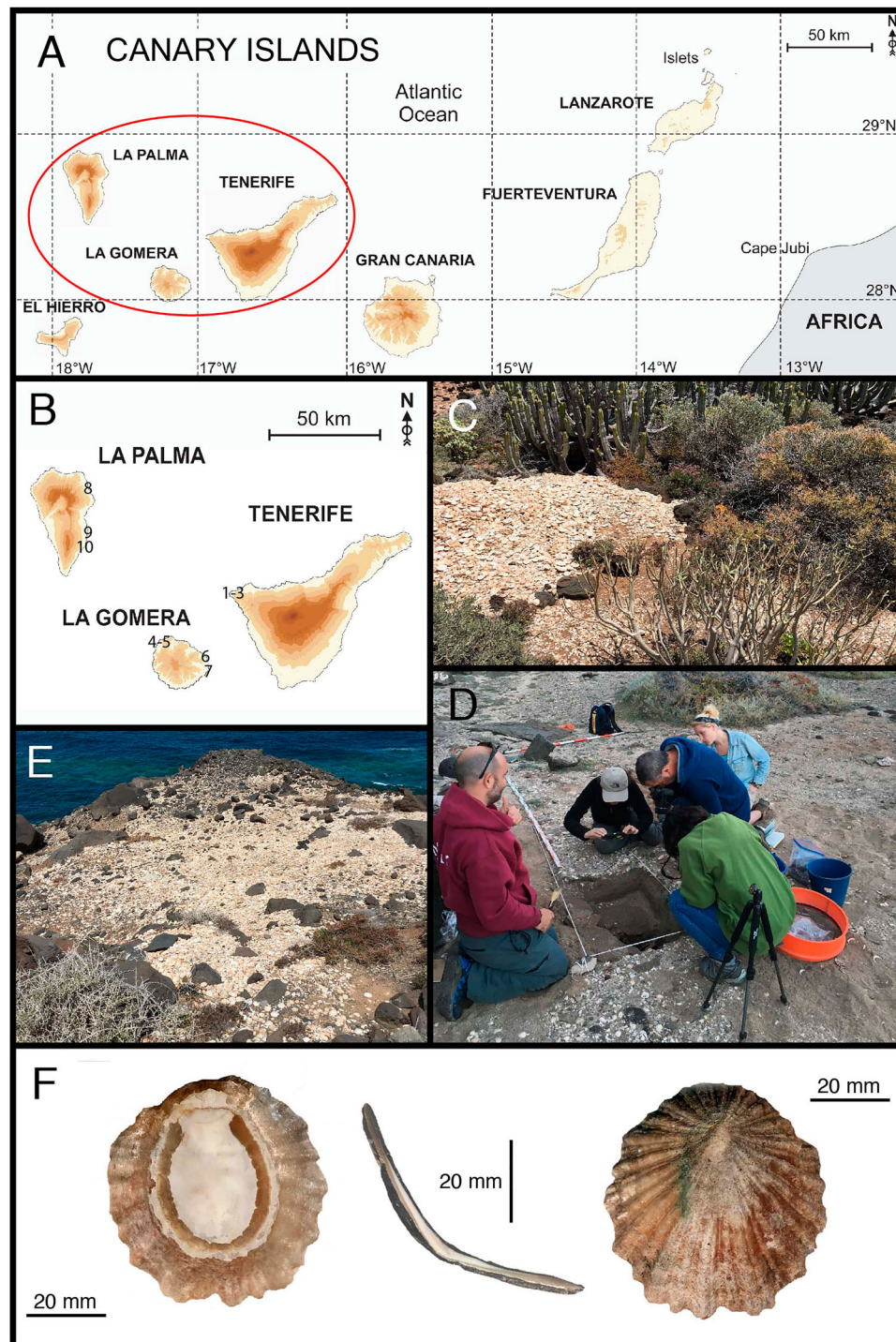
A recently published modern calibration study conducted in the Canary Islands demonstrated that the oxygen isotope ratios of the last growth episode (shell margin) of *Patella candei* d'Orbigny, 1840 can be credibly used as a paleothermometer in the archipelago (Parker et al. 2017). This study, however, found that *P. candei*  $\delta^{18}\text{O}$  values were  $1.3 \pm 0.2\text{‰}$  higher than expected when compared to predicted values if the organism precipitated its shell in isotopic equilibrium. This isotopic offset resulted in estimated SSTs that were, on average,  $5.7 \pm 0.6^\circ\text{C}$  lower than observed values if not corrected. However, because the vital effect is uniform and predictable, it can be corrected by subtracting  $1.3\text{‰}$  from the measured shell  $\delta^{18}\text{O}$  value. Similar offsets have been documented in other *Patella* species that serve as archives of SST (Shackleton 1973; Cohen and Tyson 1995; Fenger et al. 2007; Wang, Surge, and Mithen 2012; Surge et al. 2013; Gutiérrez-Zugasti et al. 2017; Prendergast and Schöne 2017). The adjusted temperatures from the shell coincided well with observed SST in the study area during the time of collection. Accordingly, archaeological *P. candei* shells from the Canaries should provide credible SST estimates after offset correction (Parker et al. 2017).

Changes in body size through time have been used to assess intensity of shellfish predation across the globe, from archaeological sites in Denmark, Scotland and Iberia (Andersen and Rasmussen 1991; Russell, Bonsall, and Sutherland 1995; Bailey and Craighead 2003; Milner, Barrett, and Welsh 2007) to Japan, South Africa, and New Zealand (Swadling 1976; Koike 1986; Klein and Steele 2013). There is a wide variety of factors that can affect intertidal mollusc growth rates, which include variations in salinity and turbidity, as well as water temperature, mollusc population density, and overall biological community composition (Klein and Steele 2013). Of these factors, mollusc population density and community composition are known to be particularly affected by human interference in prehistoric times. Temperature, salinity, and other natural factors must also be considered when assessing changes in body size over time. However, temporal and spatial averaging of shell middens may limit our ability to properly assess the effect of these natural factors on the composition of shelly material accumulated in space and time (Klein and Steele 2013). Additionally, since salinity and temperature

are likely to have remained relatively consistent in the Canary Islands over the last two millennia, due to their low-latitude location and absence of inflowing freshwater sources, studies conducted in these locations are expected to be primarily influenced by human-mollusc interactions (Mann and Jones 2003; Lebreiro et al. 2006). Modern populations in the Canary Islands are one of the few remaining human groups that continue to utilise limpets as a major dietary staple. Therefore, human-mollusc interactions for gastronomic purposes are not limited to the archaeological record in the Canary Islands, but rather are an ongoing process continuing to the present.

In this study, we investigate 10 well-preserved and physically accessible shell middens from 3 of the 7 Canary Islands of Spain: Tenerife, La Palma and La Gomera (Figure 1(B)). There are three primary objectives to this study. First, we determine the ages of 10 archaeological sites using AMS radiocarbon dating on the shells themselves, providing the first numerical ages for most of the studied sites. Second, we analyse the oxygen isotope composition of the shell margin of archaeological *P. candei* to produce an exploratory dataset of the temperatures closest to the time of shellfishing practices, which will subsequently form the basis for ongoing and future high-resolution seasonality studies throughout the archipelago. Third, we attempt to assess the intensity of shellfishing practices, and their long-term ecological impacts, through the analysis of changes in body size through a time of modern and archaeological adult specimens.

There are two driving hypotheses for this research. First, it is hypothesised that shellfish were not exploited year-round because the moist/cool conditions of the winter seasons would have promoted inland agriculture and increased the availability of pastures for livestock, thus reducing aboriginal reliance on marine resources during the wettest and greenest part of year. It is possible that marine resource reliance will vary from island to island, as some islands had significant agriculture and livestock, and therefore the populations of that island may have only shellfished provisionally, while others relied more heavily on 'hunter-gatherer' subsistence strategies, and may have shellfished more continuously throughout the year. The second driving hypothesis is that shell size of limpets from the Canary Islands have declined, primarily in response to increasing human harvesting practices from aboriginal times to the present. This second hypothesis derives from archaeological research elsewhere which suggest that increased human harvesting practices consistently results in reduced shell size (Klein and Steele 2013). This is because the most edible molluscs (the larger and older organisms) are more intensively collected, which, in turn, diminishes turnover rates due to resource depression (Klein and Steele 2013). Resource depression is defined by Charnov,



**Figure 1.** (A) The Canary Archipelago relative to Northwest Africa; focal islands denoted in the ellipse. (B) The focal islands with the locations of the archaeological sites numbered 1–3 (Teno Bajo), 4–5 (Arguamul), 6 (Barranco del Águila), 7 (Puntallana), 8 (Cueva del Tendal), 9 (La Salamera) and 10 (Roque de Los Guerra). (C) A shell midden from Teno Bajo, Tenerife. (D) Excavations at Puntallana, La Gomera. (E) Shell midden at Arguamul 2, La Gomera. (F) Left: Ventral view of an archaeological *P. candei* shell (anterior on top, posterior on bottom); Centre: Bisected archaeological *P. candei* shell along the median sagittal plane (anterior on top, posterior on bottom) to show the layered calcium carbonates – Calcite (grey) and Aragonite (white); Right: Dorsal view of an archaeological *P. candei* shell (anterior on top, posterior on bottom).

Orians, and Hyatt (1976) as a reduction in the availability of prey from the perspective of a predator, due, in part, to the exploitation pressures from that predator. Resource depression is a common result of harvesting pressures, and causes changes in habitat and ecological niches, which can, in turn, disrupt ecosystem balance and lead to enhanced ecological stress

(Charnov, Orians, and Hyatt 1976; Jackson et al. 2001; Klein and Steele 2013).

### Geographic, Climatic, and Geological Setting

The Canary Islands are a subtropical oceanic archipelago located approximately 90 km west of the



northwest coastline of Africa, from 27–29°N and 13–18°W (Figure 1(A)). The islands are formed from hot-spot volcanism, and the underlying geologic formations are basaltic in composition (van den Bogaard 2013). The oldest subaerial exposures in the archipelago are dated to ~23 Ma in Fuerteventura, the easternmost island (van den Bogaard 2013).

The islands have a subtropical oceanic climate characterised by low to moderate rainfall (200–700 mm/year) and mild year-round air temperatures (15–28°C) (García Herrera et al. 2001; <http://www.aemet.es/>). The Modern SSTs range from 18 to 25°C. This range is determined from monthly SSTs catalogued by the International Research Institute for Climate and Society at Columbia University ([https://iridl.ldeo.columbia.edu/maproom/Global/Ocean\\_Temp/Monthly\\_Temp.html](https://iridl.ldeo.columbia.edu/maproom/Global/Ocean_Temp/Monthly_Temp.html)) The location from which the monthly SST data was retrieved is in the open ocean off the coast of NW Tenerife island, near 28.42°N, 16.96°W. This temperature range is in agreement with the annual average temperature of 21°C observed by Parker et al. (2017).

The Canary Islands are surrounded by the Canary Current, which is a cold derivative of the Gulf Stream propagating southward along the west coast of Africa (García Herrera et al. 2001). This current brings saturated air into contact with the northern reaches of the islands, but dramatic topography causes a rain-shadow effect to occur, especially on the younger (and more rugged) western islands. Thus, there is a wide range of climate zones present throughout the archipelago, and each climate zone is the result of the confluence of geospatial location on the island as well as elevation (Bueno and Carta 2006). The Canary Islands are also subjected to the annual oscillation of the Inter-tropical Convergence Zone (ITCZ) which brings west-blowing winds carrying Saharan dust to the islands in the warmer months from May to November (Izquierdo et al. 2011).

The three islands targeted in this study are – from east to west – Tenerife, La Gomera, and La Palma (Figure 1(B)). Tenerife is the largest island in the archipelago, both by land area and elevation (2030 km<sup>2</sup> and 3718 m, respectively) (García Herrera et al. 2001; Ancochea et al. 2003). La Gomera (320 km<sup>2</sup>; 1487 m) is nearly circular in shape and is characterised by deep ‘barracks’ (gullies) and steep coastal cliffs (García Herrera et al. 2001; Ancochea et al. 2003). It is also the only island in the archipelago that does not have a recent history of volcanism (García Herrera et al. 2001). La Palma is the 5th smallest island by land area in the archipelago but the second tallest island by elevation (706 km<sup>2</sup>; 2312 m). It is characterised by a large circular depression in the centre of the island and steep topography (García Herrera et al. 2001; Sangil, Martín-García, and Clemente 2013). The oldest subaerial rock ages of the three islands range from

12 Ma in Tenerife, to 9 and 4 Ma in La Gomera and La Palma, respectively.

## Archaeological Background

The original inhabitants of the Canary Islands arrived approximately 2500 years ago by boat to the cluster of seven islands located just 90 km from the coast of modern day Morocco (Maca-Meyer et al. 2004; Fregel et al. 2009). The prevailing hypothesis regarding the origin of the aboriginal Canarian population is that the Northwest African Berber peoples migrated to islands in multiple waves prior to European settlement in the fifteenth century (Mercer 1980; Flores et al. 2001). This hypothesis is supported by recent mtDNA analysis of aboriginal remains, which found that the Berbers are the primary genetic ancestor of the aboriginal Canarians, with 42–78% of their genetic material in common (Pinto et al. 1996; Rando et al. 1999; Maca-Meyer et al. 2004). The remaining percentages tie in to the Mediterranean European region, as well as near eastern peoples from Asia (Fregel et al. 2009). Prior to European expansion into the archipelago, there is little evidence of interisland migration or communication, as Europeans encountered a population with limited knowledge of seafaring techniques (Mercer 1980). Genetic diversity studies have been conducted to determine genetic similarity (or dissimilarity) between the inhabitants of different islands (Maca-Meyer et al. 2004; Fregel et al. 2009). These studies support that some interisland migration may have occurred, as there are strong genetic similarities between different island groups. However, this lower-than-expected genetic diversity could also be explained by common ancestry, so additional studies on the genetic lineages of the Canarian peoples are being conducted (Maca-Meyer et al. 2004; Fregel et al. 2009).

While each island developed from the same ancestral population, the lack of interisland communication and ecological differences between islands resulted in drastically different agricultural development, hierarchical social systems, and resource exploitation practices (Arnay-de-la-Rosa et al. 2009). The larger central islands of the archipelago (Gran Canaria and Tenerife) had more developed agriculture than either the arid eastern islands or the rugged western islands (Arnay-de-la-Rosa et al. 2009, 2010), which relied more heavily on livestock. On the island of Tenerife, which hosted between 15 and 20 thousand aboriginal inhabitants, agriculture and goat farming dominated the economic landscape, due to larger expanses of open land and more grazing options when compared to the smaller western islands (Arnay-de-la-Rosa et al. 2010). The diet of aborigines from Tenerife was mixed, with both large agricultural contribution as well as shellfishing and meat consumption (Aufderheide et al. 1992;

Maca-Meyer et al. 2004; Arnay-de-la-Rosa et al. 2010). As such, the rates of osteopenia were lower than on Gran Canaria, which had a larger human population and was more reliant on agriculture. Agricultural practices were not as extensive in the smaller western Canary Islands (González-Reimers et al. 1991; Arnay-de-la-Rosa et al. 2010). The western islands, including La Palma and La Gomera, had significantly smaller populations than the larger central islands, with La Gomera hosting only 2000–2500 residents at the time of Hispanic contact (Arnay-de-la-Rosa et al. 2009). The aboriginal populations of La Gomera and La Palma subsisted primarily on goat herding and marine resource exploitation, with rudimentary agriculture consisting primarily of barley cultivation (Maca-Meyer et al. 2004; Arnay-de-la-Rosa et al. 2009, 2010).

Large accumulations of marine shells, from subsistence shellfishing, are present at coastal sites throughout the archipelago, including Tenerife, La Gomera and La Palma. These accumulations, often known as ‘middens’ are overwhelmingly dominated by limpets of the *Patella* genus, including *Patella aspera* and *P. candei*, as well as other gastropods such as *Phorcus atratus* Wood, 1828 and *Stramonita haemastoma* Linnaeus 1767 (formerly *Thais haemastoma*). In some residential/kitchen middens (trash deposits from dwellings) from La Palma, the bones of goats (*Capra hircus*), pigs (*Sus scrofa*), and short-haired sheep (*Ovis aries*) can be found alongside coastal fish and shellfish.

Throughout time, societal structures often become more hierarchical with increasing population, this can be observed in the Canary Islands as well. The largest island by population, Gran Canaria, had the most advanced agriculture and a well-developed social hierarchy (Arnay-de-la-Rosa et al. 2010). The western islands, however, were far less populous, more dependent on livestock, and exhibited more egalitarian (less hierarchical) social structures.

### Ecology and Morphology of *P. candei*

Gastropods of the genus *Patella* Linnaeus 1758 (Gastropoda: Patellidae) are primarily stationary to slow-moving browsers found within the rocky intertidal and infratidal regions of the Atlantic and Mediterranean coasts of Africa and Europe. The family Patellidae can be found farther afield, including in the Americas and in New Zealand (Branch 1971). *Patella* attaches to the rocky surfaces in the intertidal and only moves from its ‘home scar’ to make short grazing trips before returning (Branch 1971). They consume algae, diatoms, and lichen and therefore are zoned vertically to reduce competition for food (Branch 1971).

The genus *Patella* has been observed to reduce shell growth rates during summer months and completely cease shell growth in the winter months at high

latitudes (Fenger et al. 2007; Surge et al. 2013; Wang, Surge, and Walker 2013). In contrast, recent low-latitude studies have observed that *P. candei* in the Canary Islands appears to grow year-round without evidence of complete growth cessation (Parker et al. 2017).

*P. candei*, like other members of the genus, is characterised by a concave and elliptical shell with a subcentrally located apex and iridescent interior (Figure 1(F)). Shell ornamentation is in the form of radiating lirae and concentric growth rings (Wang, Surge, and Mithen 2012) (Figure 1(F)). Shells of *P. candei* are distinguishable from the shells of the closely related *P. aspera* due to their rounded margin, thinner shell, and slightly darker colour (Riera et al. 2016). Patellid gastropods precipitate calcite at the shell margin, but crossed lamellar aragonite layers are present near the myostracum where the organism attaches to the shell (MacClintock 1967). Several published studies have determined that various species of the genus *Patella*, including *P. candei*, are reliable archives for paleoclimate information, and their stationary ecology makes them ideal candidates for paleoclimate studies in discrete locations (Fenger et al. 2007; Andrus 2011; Surge et al. 2013; Wang, Surge, and Walker 2013; Gutiérrez-Zugasti et al. 2017; Parker et al. 2017; Prendergast and Schöne 2017).

*P. candei* has undergone several taxonomic name changes in recent years, and has several synonymised names including *P. chlorostica* Gmelin, 1791, *P. crenata* Gmelin, 1791, *P. tenuis* Gmelin, 1791, *P. gomesii* Drouet, and 1858, *P. teneriffae* Mabilie, 1888. Some debate still exists about whether or not morphological variability within *P. candei* merits distinct subspecies classifications, but classification at the subspecies level is not relevant to this study. For this paper, we use *P. candei*, following the World Register of Marine Species (WoRMS) (Bouchet and Gofas 2013; WoRMS Editorial Board 2018).

### Methods

#### Description of Archaeological Sites

Sampling sites were excavated by our research group in the summer of 2016 and were classified into two distinctive categories: residential middens and shell middens. Residential middens (also called kitchen middens) are located farther inland, and represent the kitchen/cooking area of a dwelling (Jerardino 1998). These middens have a well-preserved stratigraphy that is several metres thick, and contain a variety of archaeological items, including shells, pottery, ash, charcoal, and bones. Shell middens are composed almost entirely of marine mollusc shells (Genera: *Patella*, *Phorcus*, *Thais*) with occasional terrestrial shells (Genera: *Caracolina*, *Canariella*) and are located close to shore (Figure 1(C)–(E)). All investigated

middens in the Canary Islands are dominated by the gastropod genus *Patella*, which is the focal taxon of this study. Additional information regarding all archaeological sites excavated and investigated in this study, including geographic coordinates, can be found in Table 1.

On Tenerife, all three selected sites were located on the Teno peninsula in the northwest of the island (Figure 1(C)). More than 50 shell middens exist along the peninsula known as Teno Bajo. Teno Bajo is part of the greater archaeological province of Buenavista del Norte, which encompasses multiple sites in the northwest of the island. These sites, some of which have been extensively studied, include la Cueva de Arenas, la Cueva de las Fuentes, la Cueva de Estacas, and Punta Negro/Tinajero (Mesa Hernández 2006, 2008). Throughout the Buenavista del Norte region there is a varied typology of archaeological deposits, and their stratigraphy constitutes one of the main criteria used to categorise the typology of each site. Local archaeologists interpret the sites studied here as phases of one-time intensive shellfish collections, due to their poor stratigraphy, shallow depth, and uniformity of shells present. The archaeological sites utilised in the present research are, therefore, interpreted to be the result of 'one-time' shellfishing event in that location, and thus, in-situ shells at that midden are assumed to represent one discrete period of collection (Mesa Hernández 2006, 2008).

The 3 target sites were selected from the 50 possible middens by drawing a transect from the northwest to the southeast of the peninsula, connecting the 2 farthest apart middens and then sampling the 2 termini and 1 midden approximately central on the transect. The three selected sites were named Teno Bajo numbers 42, 18, and 9 (Figure 1(B, C)). All three sites are located 6 m above mean sea level (m a.s.l.).

Teno Bajo 42, level 1 (TTB 42/1) is the north-westernmost midden sampled at Teno and has two poorly stratified layers, but the upper level had few shells in-situ. Therefore, shells were collected from the bottom layer present at the midden. The second midden sampled, and the south-easternmost site on the Teno peninsula, was Teno Bajo 18 (TTB 18), which consisted of only one stratigraphic layer. The third midden is between the previous two sampled middens, and is named Teno Bajo 9, Section B (TTB 9B). In this case, the midden is divided into two distinct groups along an east-west transect with an area devoid of shells between 9A and 9B. TTB 9A was also sampled, but the shells were too fragmented for proper body size or shell margin isotope analysis, so only 9B is used in this study.

On La Gomera, the four selected sites are divided into two geographic groups, the Northwest group and the Southeast group. In the Northwest are the sites of Arguamul 2 and 3. Arguamul 2 (GAR 2) is located

on top of a small cliff (25 m a.s.l.) and has no visible stratigraphy. Arguamul 3 (GAR 3) is located along the same cliff, however, GAR 3 is only accessible from the cliff face where erosion has exposed a shell-rich layer.

In the southwest of La Gomera, we excavated the sites of Puntallana and Barranco del Águila. Puntallana (GPLL (6)) is the only site on La Gomera to exhibit some stratigraphy. Between three and six distinct layers are present. Samples were collected from each layer, but layer six – at the bottom of the stratigraphy – was selected for analysis due to higher quality preservation and abundant shells, with no evidence of shell reworking. The second site, Barranco del Águila (GEA), is located 19 m and has no marked stratigraphy, representing one-single shellfishing event.

The three sampled sites in La Palma were all located along the east coast of the island. The farthest north of the sites is Cueva del Tendal, level III (PCT (III)), which is a residential cave and midden located at an elevation of 410 m and farther from the coastline. The second sampled site was Roque de Los Guerra, level one (PRG (1)), a small residential cave that is suspected to be one of the oldest sites in the entire archipelago. The site is located 10 m a.s.l. and has the most distinct stratigraphy of the middens studied. The residential midden itself was composed primarily of ash, presumably from cooking fires, and contained shell remains (both burned and unburned) as well as bones, charcoal, and small pottery fragments. The midden was divided into four distinct horizons, and all horizons were sampled; however, the bottom horizon – Level 1 – had the largest volume of unbroken and unburned shelly material, and therefore is the level analysed in this study. The third archaeological site, located in the southeast of La Palma, is La Salamera (PSA), which is a shell midden located at 10 m of elevation under a rocky overhang directly accessible from the beach. The midden is composed primarily of *P. candei*; however, some small rodent bones were also recovered during field excavation.

### Field Collection Methodology

Sites were sampled following established archaeological excavation techniques under the direction of local archaeologists and co-authors of this study Eduardo Mesa-Hernández, Juan Carlos Hernández-Marrero, and Jorge Pais, on Tenerife, La Gomera, and La Palma islands, respectively (Figure 1(D)). In-situ bulk shell samples were collected in stratigraphic and spatial order from the selected middens and placed into plastic bags labelled with the site and level, if applicable. In the cases where stratigraphic differentiation of layers was present (such as with residential middens), each level was excavated independently and put into different plastic bags, with the level numbers ascending from

**Table 1.** Field sites.

Island	Site name	Focal level	Site abbreviation	Elevation (m)	Latitude (°N)	Longitude (°W)	Type of deposit
Tenerife	Teno Bajo 9B	~	TTB 9B	26	28.35485	16.92206	Shell Midden
Tenerife	Teno Bajo 18	~	TTB 18	27	28.35220	16.92294	Shell Midden
Tenerife	Teno Bajo 42/1	~	TTB 42/1	63	28.36296	16.89895	Shell Midden
La Gomera	Arguamul 2	~	GAR 2	25	28.20694	17.30123	Shell Midden
La Gomera	Arguamul 3	~	GAR 3	5	28.20391	17.30515	Shell Midden
La Gomera	Barranco del Águila	~	GEA	19	28.13544	17.11436	Shell Midden
La Gomera	Puntallana	Level 6	GPLL (6)	32	28.12859	17.10510	Shell Midden
La Palma	Cueva del Tendal	Level III	PCT (III)	410	28.78643	17.76632	Residential Midden
La Palma	La Salamera	~	PSA	10	28.60460	17.75986	Shell Midden
La Palma	Roque de Los Guerra	Level 1	PRG (1)	10	28.56745	17.76415	Residential Midden
Tenerife	Modern	~	LC	0	28.29472	16.37389	Live-Collected

bottom to top of the midden. The depth and maximum length and width of the sites were taken using a tape measure, and GPS coordinates and elevation were taken using a Garmin etrex® 20x GPS. At one site, Cueva del Tendal on La Palma island, collections were conducted at the Museo Arqueológico Benahorita in collaboration with local archaeologist Jorge Pais, as the material had been previously excavated by prior archaeological teams studying the site. All shells used in this study were excavated at the same time in 1977 and were all recovered, in-situ, from level III of the site. Soler Javaloyes et al. (2002) describes additional information about the archaeological practices and procedures used in the original excavation.

Modern shells for body-size analysis were originally live-collected by co-author Yurena Yanes and local field assistant Julio Yanes in the harbour of Puertito de Güímar (east of Tenerife). A description of the collection methodology for these shells can be found in Parker et al. (2017). There are no rivers providing freshwater or sediment input to the harbour, motorised watercraft are prohibited from entering the harbour and the nearby marina (a possible source of oil contamination from boats) is located 600 m Southwest of the sampling site and does not directly access the harbour. Adult and largest specimens were preferentially selected and gathered during modern sample collection. Hence, it is assumed that this potential sampling bias towards the largest specimens of living limpet populations should be comparable to the bias during aboriginal times. Upon collection, both modern and archaeological shells were carefully packaged and shipped to the University of Cincinnati for subsequent laboratory analyses.

### Sample Preparation and Laboratory Analyses

#### AMS Radiocarbon Dating of Shells

One shell from each of the 10 sampled field sites was selected for AMS <sup>14</sup>C dating. Dated shells were also analysed isotopically together with another nine shells from the same stratigraphic layer. Because all shells from each site were collected in-situ from the same shell horizon, it is assumed that analysed shells from each field site and level are the same age.

A portion of the 10 selected limpet shells were dated at the W. M. Keck Carbon Cycle AMS Facility at the University of California Irvine. Samples were washed with deionised water to remove detrital contaminants and then leached in dilute HCL to remove secondary carbonate. To produce CO<sub>2</sub>, the shells underwent an acid hydrolysis procedure, with 85% phosphoric acid in disposable septum-sealed reactors. CO<sub>2</sub> was reduced to graphite with hydrogen and an iron powder catalyst at 560°C. In this process Mg(ClO<sub>4</sub>)<sub>2</sub> is used to remove water. Samples processed in this lab using this method have exhibited 0.3% precision and 55,000 yr backgrounds (<https://www.ess.uci.edu/group/ams/facility/ams>; Culleton et al. 2006). Radiocarbon dates were calibrated using the MARINE13 calibration curve CALIB 7.1 (<http://calib.org/calib/calib.html>). The marine reservoir effect (ΔR) was corrected using data from the Marine Reservoir Correction Database ([www.calib.org/marine](http://www.calib.org/marine)). ΔR was determined to be 135 ± 103 years, calculated using geographic proximity to studies of the reservoir effect by Ndeye (2008) and Monges Soares (1993) in nearby Senegal and Iberian Spain, respectively. The samples were corrected for <sup>13</sup>C fractionation per the conventions of Stuiver and Polach (1977). Calibrated radiocarbon ages are reported using the 2-sigma (2σ) age range to ensure a 95.4% probability that the real age falls within the range of the radiocarbon ages (Table 2).

#### Stable Oxygen Isotopes

Ten shells from each sampled stratigraphic horizon (*n* = 100 shells total) were selected for isotopic analysis. Measured shells were adult (mature) specimens that exhibited pristine shell margins. A Dremel® 4000 dental drill was used to sample the outermost edge of intact shells, representing the last growth episode of the shell. Shell powder was collected at the Center for Stable Isotopes, the University of New Mexico following Spötl and Vennemann's (2003) protocol. Samples were analysed isotopically on weighing paper and then transferred to 0.5 mL polypropylene microcentrifuge tubes. Carbonate powder samples were loaded in 12 mL borosilicate exetainers, flushed with He and reacted for 12 h with H<sub>3</sub>PO<sub>4</sub> at 50°C. The evolved CO<sub>2</sub> was measured by continuous flow Isotope Ratio



**Table 2.** Calibrated radiocarbon ages for 10 archaeological sites across 3 of the Canary.

AMS Lab No.	Sample ID	Field site	Island	<sup>14</sup> C age	±	Fraction modern	Calibrated ages			
							2-Sigma (BP)	Median (BP)	2-Sigma (AD/BC)	Median (AD/BC)
176111	PRG(1)-1	Roque de Los Guerra	La Palma	2335	15	0.7475	1540–2050	1800	BC 100–AD 400	AD 150
176113	TTB(42/1)–1	Teno Bajo 42/1	Tenerife	2075	15	0.7723	1280–1730	1500	AD 220–670	AD 450
176112	TTB(9B)–1	Teno Bajo 9B	Tenerife	1815	15	0.7979	990–1460	1250	AD 490–960	AD 700
176114	TTB(18)–1	Teno Bajo 18	Tenerife	1780	15	0.8011	960–1390	1200	AD 560–1000	AD 750
176109	PSA-1	La Salamera	La Palma	1570	20	0.8226	760–1220	1000	AD 730–1190	AD 950
176110	PCT(III)–1	Cueva del Tental	La Palma	1550	15	0.8246	730–1100	970	AD 760–1220	AD 980
176107	GPLL(6)–1	Puntallana	La Gomera	1435	15	0.8364	650–1060	850	AD 890–1300	AD 1100
176106	GAR(3)–1	Arguamul 3	La Gomera	1320	15	0.8484	550–930	750	AD 1020–1400	AD 1200
176105	GAR(2)–6	Arguamul 2	La Gomera	1015	15	0.8815	300–650	500	AD 1300–1650	AD 1450
176108	GEA-1	Barranco del Águila	La Gomera	510	15	0.9383	≤1300	~500	≥AD 650	~AD 1450

Mass Spectrometry using a Gasbench device coupled to a Thermo Fisher Scientific Delta V Plus Isotope Ratio Mass Spectrometer. The results are reported using delta notation ( $\delta^{18}\text{O}$ ), versus VPDB (Vienna Pee Dee Belemnite). Reproducibility was greater than 0.1‰ for  $\delta^{18}\text{O}$  based on repeats of a laboratory standard (Carrara Marble). The laboratory standard was calibrated versus NBS 19, for which the  $\delta^{18}\text{O}$  is  $-2.2\text{‰}$ . The shell margin  $\delta^{18}\text{O}$  values are corrected for the known vital effect for the target species by subtracting 1.3‰ (Parker et al. 2017).

SST closest to the organisms' death (i.e. closest to harvesting time) was calculated from shell margin  $\delta^{18}\text{O}$  values using the calcite equilibrium fractionation equation for calcite and water from Friedman and O'Neil (1977) modified from Tarutani, Clayton, and Mayeda (1969):

$$1000\ln\alpha = 2.78 \times 106/T^2 - 2.89, \quad (1)$$

where  $\alpha$  is the fractionation factor between calcite and water, and  $T$  is temperature in Kelvin. The relationship between  $\alpha$  and  $\delta$  is

$$\alpha = (\delta^{18}\text{O}_{\text{calcite}} + 1000)/(\delta^{18}\text{O}_{\text{water}} + 1000), \quad (2)$$

where  $\delta$  is presented in Vienna Standard Mean Ocean Water (VSMOW). Conversion between VPDB and VSMOW followed the equation by Coplen, Kendall, and Hopple (1983) and Gonfiantini, Stichler, and Rozanski (1995):

$$\delta^{18}\text{O}_{\text{VSMOW}} = (\delta^{18}\text{O}_{\text{VPDB}} \times 1.03091) + 30.91 \quad (3)$$

### Body Size

The 100 shells used for isotopic analysis were also measured along 3 growth directions, using a digital caliper with a resolution of 0.01 mm. The maximum length (Y-axis), maximum width (X-axis), and maximum height (Z-axis) were all tabulated for all 100 shells. Additionally, 80 modern adult shells that were live-collected between 2011 and 2012 at Puertito de

Güímar, Tenerife Island, were measured along the same axes to provide a modern analogue to put the archaeological shells into context.

### Statistical Analyses

All statistical tests were conducted in the *PAST* 3.12 statistical modelling landscape (Hammer, Harper, and Ryan 2001). The Kruskal–Wallis test (also known as the one-way ANOVA on ranks), was used to assess potential differences among median values of groups of samples, considering statistical significance when the  $p$  value ( $\alpha$ ) was smaller than .05. Due to the multiple comparisons among sites, a Bonferroni correction was applied by dividing 0.05 by the total number of comparative tests ( $n = 55$ ), which lowered the  $p$  value to .0009. The Mann–Whitney  $U$  test (also known as the Wilcoxon rank-sum test) was also utilised to conduct pairwise comparisons to determine the significance of difference between two individual sites.

## Results

### Radiocarbon

Radiocarbon results are reported in Table 2. The oldest dated shell yielded a median probability calibrated age of 1800 cal. yrs. BP (AD 150) with a  $2\sigma$  range of 1540–2050 cal. yrs. BP (BC 100–AD 410). This shell was retrieved from the Roque de Los Guerra site, on the Island of La Palma. The youngest shell, gathered from the Barranco del Águila site on La Gomera Island, yielded an age too young to accurately determine the base of the age range. It is difficult to calibrate radiocarbon dates younger than 500 BP due to the marine reservoir effect. The shell retrieved from Barranco del Águila, when corrected for the marine reservoir effect, has a radiocarbon age below 500 BP, and therefore, the site is regarded as  $\leq 1300$  cal. yrs. BP ( $\leq$ AD 650). This site is likely much younger than this,

possibly even being deposited after the arrival of the Spanish in the archipelago, but it is not possible to determine the exact age range of the site. For this study, we will notate the age of Barranco del Águila as ~500 BP. Obtained calibrated radiocarbon results from selected limpet shells (varying between ~1800 and 500 cal. yrs. BP; AD 150–1450) overlap with much of the period of known aboriginal occupation in the archipelago, further reinforcing their archaeological origin.

### Shell Margin Oxygen Isotope Ratios

All  $\delta^{18}\text{O}$  values and calculated temperature data are presented in Table 3 and Table S1. Description and discussion of isotopic results refer to corrected values only. The minimum  $\delta^{18}\text{O}$  value ( $-1.6\text{‰}$  VPDB) was retrieved from Cueva del Tendal, on the island of La Palma. The maximum  $\delta^{18}\text{O}$  value ( $-0.1\text{‰}$  VPDB) was retrieved from two different shells, one from Teno Bajo 18 and the other from Barranco del Águila, on Tenerife and La Gomera, respectively (Figure 2). The median  $\delta^{18}\text{O}$  value for all shells studied ( $n = 100$ ) was  $-0.7\text{‰}$  VPDB. The average  $\delta^{18}\text{O}$  value was  $-0.7 \pm 0.4\text{‰}$  VPDB, showing data symmetry when compared to the median.

The maximum calculated temperature, retrieved from Cueva del Tendal, was  $26.7^\circ\text{C}$ , slightly higher than the modern average annual maximum temperature in the archipelago ( $25^\circ\text{C}$ ). The minimum calculated temperature,  $19.7^\circ\text{C}$ , was retrieved from Teno Bajo 18 and Barranco del Águila on Tenerife and La Gomera, respectively. The median calculated temperature for all shells studied ( $n = 100$ ) was  $22.3^\circ\text{C}$ . The average calculated temperature was  $22.5 \pm 1.7^\circ\text{C}$ , showing a slightly right-skewed data asymmetry when compared to the median. Temperatures recorded from archaeological shells were divided as follows: 25% between  $19.7^\circ\text{C}$  and  $21^\circ\text{C}$ , 35% between  $21^\circ\text{C}$  and  $23^\circ\text{C}$ , 33% between  $23^\circ\text{C}$  and  $25^\circ\text{C}$ , and the final 7% at temperatures that exceeded  $25^\circ\text{C}$  (Table S1).

On Tenerife, the median  $\delta^{18}\text{O}$  value of all shells ( $n = 30$ ) from the three sites is  $-0.5\text{‰}$  VPDB which corresponds to a calculated temperature of  $21.3^\circ\text{C}$ . Sidewise comparisons suggest significant difference between the studied sites (Figure 3). On La Gomera, the median  $\delta^{18}\text{O}$  value of all shells ( $n = 40$ ) from four middens is  $-0.7\text{‰}$  VPDB which corresponds to a temperature of  $22.2^\circ\text{C}$ . Comparisons among La Gomera sites suggest no significant differences (Figure 4). On La Palma, the median corrected  $\delta^{18}\text{O}$  value of all shells ( $n = 30$ ) from three different archaeological settings is  $-1.0\text{‰}$  VPDB which corresponds to a temperature of  $23.6^\circ\text{C}$ . When comparing sites within La Palma, no significant differences were observed (Figure 5). The results suggest that, on average, aborigines from La Palma collected shells during the warmest months ( $\sim 24^\circ\text{C}$ ),

followed by La Gomera aborigines ( $\sim 22^\circ\text{C}$ ) and finally, aborigines from Tenerife, who harvested shells during still warm but cooler conditions than other island inhabitants ( $\sim 21^\circ\text{C}$ ).

### Body Size

Body-size measurements of archaeological shells are presented in Table 4 and Table S2 whereas size data of live-collected specimens are presented in Table 4 and Table S3.

Although three bidimensional shell measurements were collected (length, width, height), they all positively correlated with each other, offering the same information. For simplicity and comparative purposes with other studies, we selected shell length, defined as the length of the maximum growth axis along the median sagittal plane (posterior to anterior), to examine potential spatial and temporal variations in shell size. The 100 archaeological measured shells show significant shifts in body size through time (Figure 6; TS1), with the lowest size being 35.09 mm from the oldest site at Cueva del Tendal, La Palma, and the largest being 69.89 mm from Puntallana, La Gomera (Table S2). The median archaeological shell size is 52.26 mm, and the average shell size is 52.07 mm. The 88 measured modern shells, however, only ranged from 24.52 to 57.41 mm (Table S3). The median shell size for the modern specimens was 36.73 mm, and the average was 37.87 mm. Average modern shells are 27% smaller than archaeological specimens (Table 4).

Mann–Whitney pairwise comparisons are presented in Table 5, which includes a total of 55 comparisons. Modern shells show a significant difference in all comparisons except those with Cueva del Tendal and Teno Bajo 18 after Bonferroni correction. On Tenerife, Teno Bajo 18 exhibits a statistically significant difference from Teno Bajo 42/1 and 9B. On La Gomera, Barranco del Águila is significantly different from the other sites on the island. Additionally, there is a significant difference between Puntallana and Arguamul 2. There is no significant difference among sites on the island of La Palma.

## Discussion

### Chronological Context

This study presents a new suite of AMS radiocarbon ages for 10 cultural shell and residential middens in three western Canary Islands (Table 2). Our ages match well with the expected ages for aboriginal occupation in these islands. The Teno Bajo sites on Tenerife have never been radiocarbon dated before, however, other sites within the Buenavista del Norte archaeological province were dated using radiocarbon analysis on charcoal and burned bone material from rock

**Table 3.** Average shell margin  $\delta^{18}\text{O}$  values, corrected  $\delta^{18}\text{O}$  values, and calculated SSTs with maximum and minimum values for each archaeological site.

Site name	Median age (cal. yrs. BP)	Avg. shell margin $\delta^{18}\text{O}$ ‰ (VPDB)	Avg. corrected $\delta^{18}\text{O}$ (−1.3‰)	Avg. calculated temperature (°C)	Site maximum (°C)	Site minimum (°C)
Barranco del Águila	~500	0.7	−0.6	22.1	24.1	19.7
Arguamul 2	500	0.7	−0.6	22.0	23.3	20.4
Arguamul 3	750	0.6	−0.7	22.3	24.3	20.7
Puntallana	850	0.6	−0.7	22.4	23.8	21.0
Cueva del Tendal	970	0.3	−1.0	24.0	26.7	20.0
La Salamera	1000	0.6	−0.7	22.5	24.4	20.5
Teno Bajo 18	1200	0.9	−0.4	20.7	21.9	19.7
Teno Bajo 9B	1250	0.9	−0.3	20.8	21.8	19.8
Teno Bajo 42/1	1500	0.0	−1.2	24.9	26.0	23.5
Roque de Los Guerra	1800	0.4	−0.9	23.2	24.3	21.3

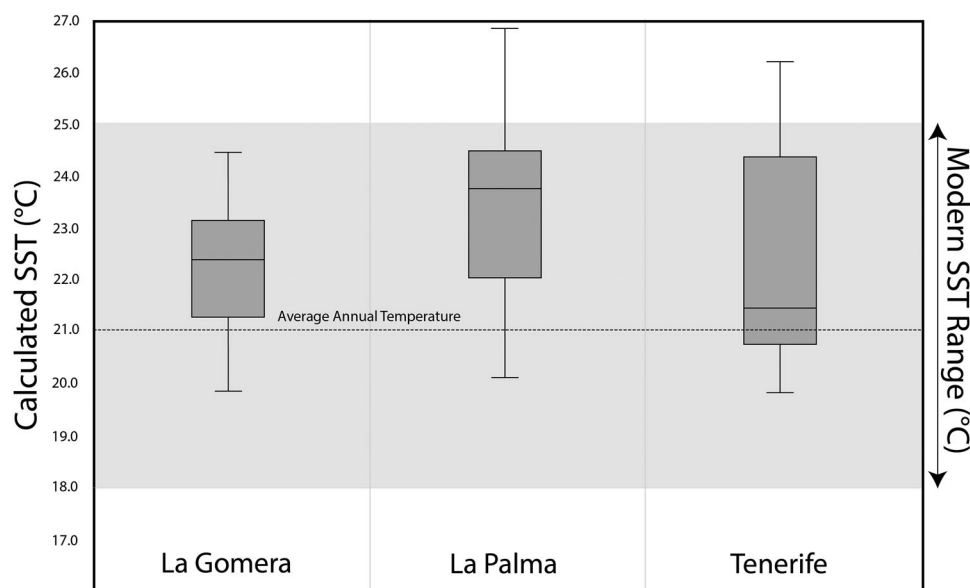
Note: The full dataset can be accessed in Supplementary Table S1.

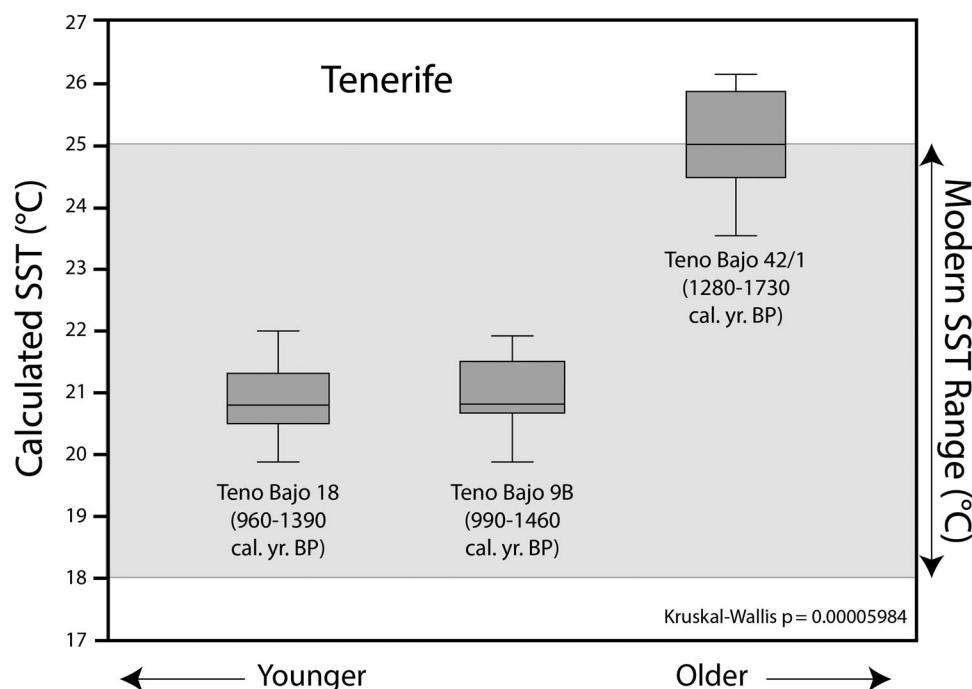
shelters and middens. For comparison with our newly dated and calibrated shell ages, all radiocarbon ages from published work in the archipelago were recalibrated using CALIB 7.1 in 2017.

On Tenerife, La Cueva de Arenas 1 site, Level III, had burned bone material from the invasive Black Rat, *Rattus rattus*, radiocarbon dated between ~470 and ~300 cal. yrs. BP (1480–1640 cal. yrs. AD) (Rando et al. 2014). *R. rattus* was introduced by European settlers in the mid 1500 s, therefore placing the latest occupation of Arenas I after the introduction of the Spanish (Rando et al. 2014). Additional radiocarbon dates of charcoal from Icod de los Vinos in northern Tenerife puts aboriginal inhabitation between 1070 and 1530 cal. yrs. B.P (420–880 cal. yrs. AD) (Arco Aguilar et al. 1997). Radiocarbon ages of human bones from Buenavista del Norte yielded a result of 1300–1520 cal. yrs. BP (430–650 cal. yrs. AD) (Galván et al. 1992). The wide range of radiocarbon dates collected from Buenavista del Norte from previously published work demonstrates that this region of Tenerife hosted aboriginal populations for much of the aboriginal inhabitation of the islands, and the new reported dates from our study (950–1730 cal. yrs. BP) continue to reinforce this interpretation.

On the island of La Gomera, the shell midden Arguamul 2 had shell material previously dated by Navarro Mederos et al. (2001) at  $280 \pm 60$  cal. yrs. BP. Our study showed Arguamul 2 to be 300–650 cal. yrs. BP, strongly overlapping with the earlier dates obtained by Navarro Mederos et al. (2001). The other northwest La Gomera site, Arguamul 3, was buried deeper than Arguamul 2, and therefore, as expected, the ages are older, ranging from 550 to 930 cal. yrs. BP. From these studies, it can be reasonably concluded that northwest La Gomera was a site of extensive shellfishing practices (and subsequent shell midden generation) for approximately 650 years – 1020–1670 cal. yrs. AD – leading up to, and slightly overlapping with, the introduction of European settlers in the 1500 s.

On La Palma island, a previous study by Soler Javaloyes et al. (2002) radiocarbon dated charcoal from the same stratigraphic level of Cueva del Tendal and obtained an age of 1270–1480 cal. yrs. AD (470–680 cal. yrs. BP). Recalculation of their data using current CALIB 7.1 results in 500–925 cal. yrs. BP. In this study, radiocarbon dating of *P. candei* yielded a median age of 970 cal. yrs. BP, which illustrates that

**Figure 2.** Boxplot of the calculated SSTs from each of the three target islands as they related to the modern average annual SST.



**Figure 3.** Boxplot of shell-derived SSTs from the three archaeological sites on Tenerife, arranged from youngest site (left) to oldest (right).

radiocarbon ages of different materials from the same stratigraphic horizon yield similar ages, and increases the reliability of the usage of *P. candei* shells to constrain shell midden chronology.

This study establishes the first chronology for Teno Bajo 9, 18, and 42/1, as well as Arguamul 3, Puntallana, Barranco del Águila, La Salamera, and Roque de Los Guerra. Dates yielded from radiocarbon analysis of *P. candei* ranged from 1800 cal. yrs. BP to <500 cal. yrs. BP, spanning the majority of aboriginal inhabitation prior to European contact. For the sites of Cueva del Tendal and Arguamul 2, the close relationship between ages reported in the literature and those determined in this study supports the accuracy and reliability of the chronology presented in this study using archaeological limpet shells. Therefore, this study establishes a credible temporal framework within which archaeologists can interpret archaeological data across Tenerife, La Gomera, and La Palma islands.

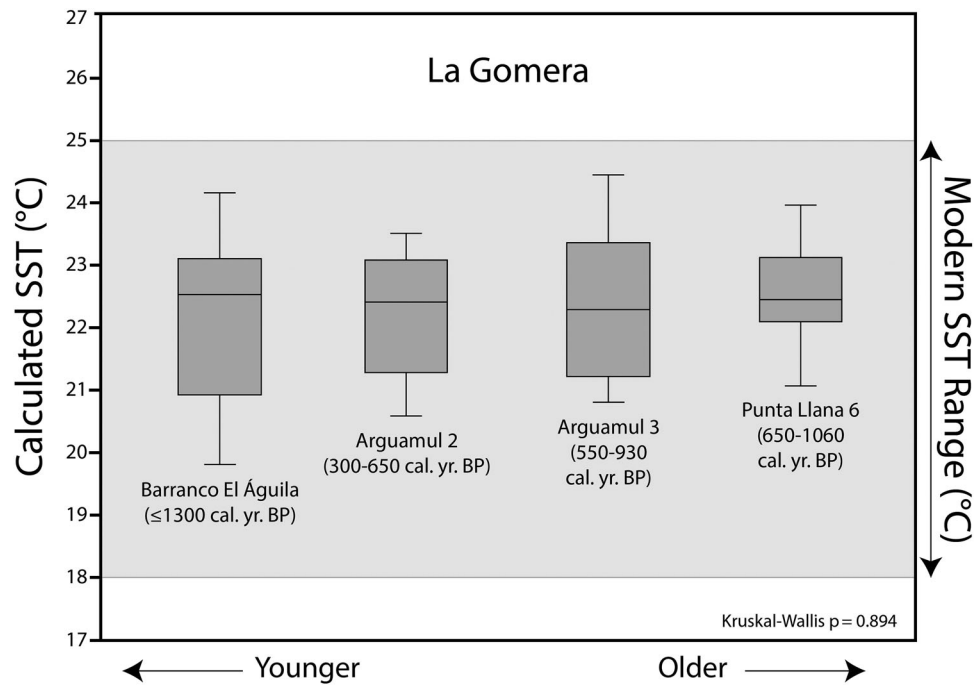
### Aboriginal Shellfish Harvesting Practices

The shell-edge data presented in this research is preliminary in nature, and its purpose is to build evidentiary support for the utility of a high-resolution sclerochronological study into the seasonality of shellfish collection. The preliminary results indicate that the aboriginal population of the Canary Islands did not collect shellfish year-round, instead preferentially collecting shellfish in the warmer part of the year only. Temperatures reconstructed from shell margin  $\delta^{18}\text{O}$  values fall overwhelmingly (75%) above the modern average annual SST of 21°C. This supports

the first driving hypothesis of this research, which stated that shellfish were not collected throughout the year (Figure 7). It has been shown that as molluscs attain older ontogenetic ages their shell growth slows. Therefore, a higher micro-drilling resolution is recommended in seasonality studies of older shells, while coarser micro-drilling resolution is acceptable for younger molluscs because they grow faster (Burchell et al. 2013). Shell margin  $\delta^{18}\text{O}$  values from live-collected adult *P. candei* shells retrieved year-round from Tenerife showed that they grow continuously year-round without any apparent deceleration or cessation during any particular season (Parker et al. 2017). Thus, even though some error is expected in the SST estimates from archaeological shell margin  $\delta^{18}\text{O}$  values, the results convincingly suggest that shellfishing practices were never executed in the coldest (SST < 21°C) months. Ongoing and future high-resolution sclerochronological work using *P. candei* shells will allow us refine the estimates of the season of collection, likely allowing us to determine the accurate month(s) of shell gathering, or even if harvesting occurred when tides were low or high.

The only two sites to exhibit median temperatures of collection below 21°C are Teno Bajo 9B and 18, with SSTs of 20.6°C and 20.7°C, respectively. These data points could represent collection during the cooler part of the year. However, there is no other archaeological evidence of a shift in subsistence strategies within the Teno Bajo region. Therefore, these anomalous data points prompted additional study into the climate system that was occurring in the northern hemisphere at the same time shells from these sites were collected,

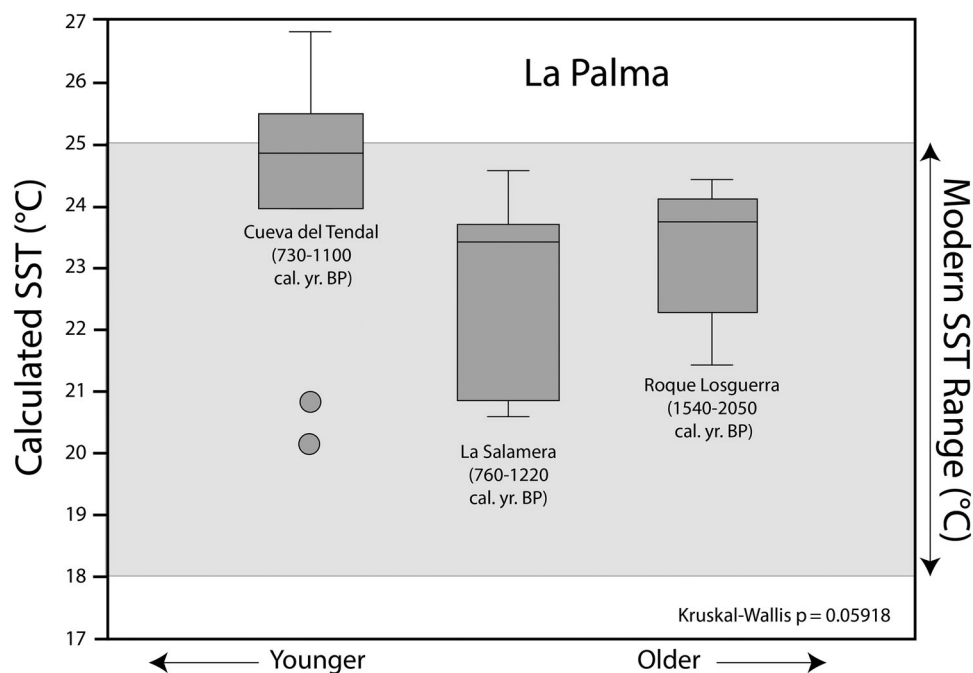




**Figure 4.** Boxplot of shell-derived SSTs from the four archaeological sites on La Gomera, arranged from youngest site (left) to oldest (right).

approximately 1200–1250 cal. yrs. BP (Figure 7). The ages from the last growth episode of shells from Teno Bajo 9B and 18 also coincide with the temporal range of the Vandal Minimum also known as the Dark Ages Cold Period (1400–1150 BP), as reported by Wang, Surge, and Walker (2013). During the Vandal Minimum, winter SSTs in coastal Florida (Latitude 25–27°N) became cooler, while summer conditions became drier (Wang, Surge, and Walker 2013). This cooling trend has been predominately observed in the western

North Atlantic, and has been shown to affect human migration patterns and shellfishing in Florida (Marquardt 2010; Wang, Surge, and Walker 2011, 2013). The Vandal Minimum has never been characterised in the eastern North Atlantic; however, the incidence of apparently anomalously low SSTs recorded at Teno Bajo during that period suggest that the potential cooling episode of the Vandal Minimum could have been present in the eastern North Atlantic. If the SSTs in the Canary Islands mirrored those in Florida during



**Figure 5.** Boxplot of shell-derived SSTs from the three archaeological sites on La Palma, arranged from youngest site (left) to oldest (right).

**Table 4.** Average length (Y-axis) measurements of archaeological and modern shells with maximum and minimum length values for each archaeological site.

Locality	Median probability age (cal. Yrs. AD)	Age (cal. Yrs. BP)	Avg. length (mm)	Site maximum (mm)	Site minimum (mm)
Barranco del Águila	~1450	~500	48.53	59.03	42.12
Arguamul 2	1450	500	57.53	60.46	49.68
Arguamul 3	1200	750	58.85	66.07	51.84
Puntallana	1100	850	62.17	69.87	57.36
Cueva del Tendal	980	970	43.81	67.69	35.09
La Salamera	950	1000	51.51	62.49	41.78
Teno Bajo 18	750	1200	43.96	49.99	40.28
Teno Bajo 9B	700	1250	50.06	58.89	40.69
Teno Bajo 42/1	450	1500	52.43	58.14	44.59
Roque Los Guerra	150	1800	51.87	63.18	44.96
Puertito de Güimar	Modern	Modern	37.87	57.41	24.52
Avg. Archaeological shell (mm)	52.07				
Avg. modern shell (mm)	37.87				
% Difference	27				

Note: The full dataset can be accessed in Supplementary Tables S2 (archaeological shells) and S3 (modern shells).

the Vandal Minimum (Figure 7), winter SSTs would be depressed by  $\sim 6^{\circ}\text{C}$  compared to their pre-Vandal Minimum temperatures (Wang, Surge, and Walker 2013). Other studies have shown that flow rates of the North Atlantic Subtropical Gyre decreased during the northern hemisphere cooling events, most notably during the Little Ice Age, with a lower magnitude decline in flow rates during the Vandal Minimum (Lund, Lynch-Stieglitz, and Curry 2006). This change in flow rates could also impact temperatures across the North Atlantic. If this is the case in the Canary Islands, it is possible that the average annual SST of the archipelago was also lower than the modern day average annual SST of  $\sim 21^{\circ}\text{C}$ , and therefore, the shells at Teno Bajo 9B and 18 may have been collected during the warmest months of the year. This possible record of the Vandal Minimum could be the first indication of this climatic event in the subtropical eastern North Atlantic, and therefore merits further extensive research to validate and constrain. Thus, the presence of a record of the Vandal Minimum will be tested in future research using isotope sclerochronology data (i.e. oxygen isotope time-series along shell growth direction) of limpet shells from the same archaeological stratigraphic layers (Figure 7).

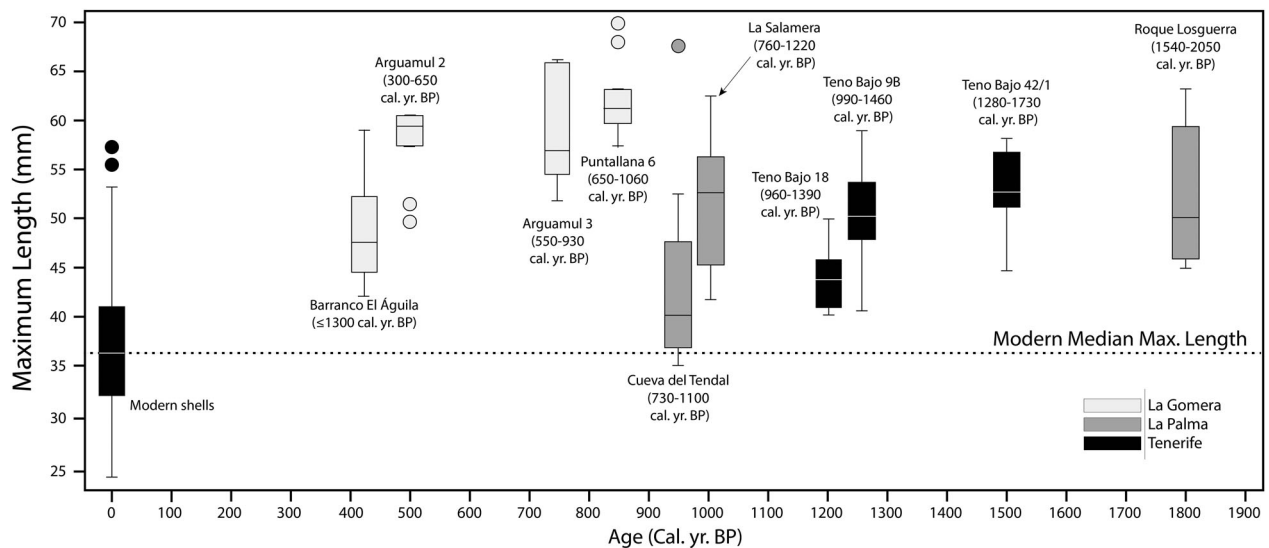
Additional study into northern hemisphere climate events that occurred between 1800 and 500 yrs. BP establishes that the shells collected in this study were likely harvested during the Roman Warm Period (1950–1400 yrs. BP) and the Medieval Climate Anomaly/Medieval Warm Period (750–1150 yrs. BP), in addition to the previously mentioned Vandal Minimum (Surge and Barrett 2012; Wang, Surge, and Walker 2013). Figure 7 depicts median temperatures calculated from shell margin  $\delta^{18}\text{O}$  values over the last two millennia, including several cooling and warming climate intervals well known for the northern hemisphere. Interestingly, the two shell middens deposited during the Roman Warm Period exhibit some of the highest temperatures in the study, while the lowest ones occurred during the Vandal Minimum. The median temperatures increase again during the

Medieval Climate Anomaly, and begin to depress again towards the end of the dataset, likely due to the onset of the Little Ice Age in the fifteenth century (1400 AD) (Mann et al. 2009) (Figure 7).

The shell-edge data presented in this research is not sufficiently robust to produce paleoclimate interpretations. In order to do so, high-resolution time-series analyses of the shells are being conducted using isotope sclerochronology. To reliably interpret seasonality signals, shells dated to all the Holocene rapid climate events (Vandal Minimum, Roman Warm Period, Medieval Climate Anomaly, and Little Ice Age) must be subjected to high-resolution time-series analyses, such as those conducted by Hallmann et al. (2009) or Surge et al. (2013). This dataset, however, does provide a convincing argument that these events may be represented in the midden record in the Canary Islands, which merits additional research.

### Comparisons with Other Atlantic Shell Middens

This research is the first preliminary assessment of shellfish collection for the aboriginal population of the Canary Islands. Other studies of seasonality have been conducted across the world, with several focused in the Atlantic basin, including in coastal regions of Sicily and Scotland. In Sicily, oxygen isotope ratios were used to determine the season of collection for the edible marine gastropod *Phorcus turbinatus* Born, 1778, at Grotto dell'Uzzo by early Mesolithic, late Mesolithic and early Neolithic human groups (Mannino et al. 2007). This study showed that *P. turbinatus* was preferentially exploited in the winter months by the early Mesolithic Sicilians, while it was exploited year-round by the late Mesolithic Sicilians (Mannino et al. 2007). The year-round exploitation transitioned to a three-season pattern by the early Neolithic groups, with the notable absence of summer exploitation (Mannino et al. 2007). Mannino et al. (2007) attributed their results to sporadic inhabitation of Grotto dell'Uzzo site, likely as a ritualistic burial site and not as

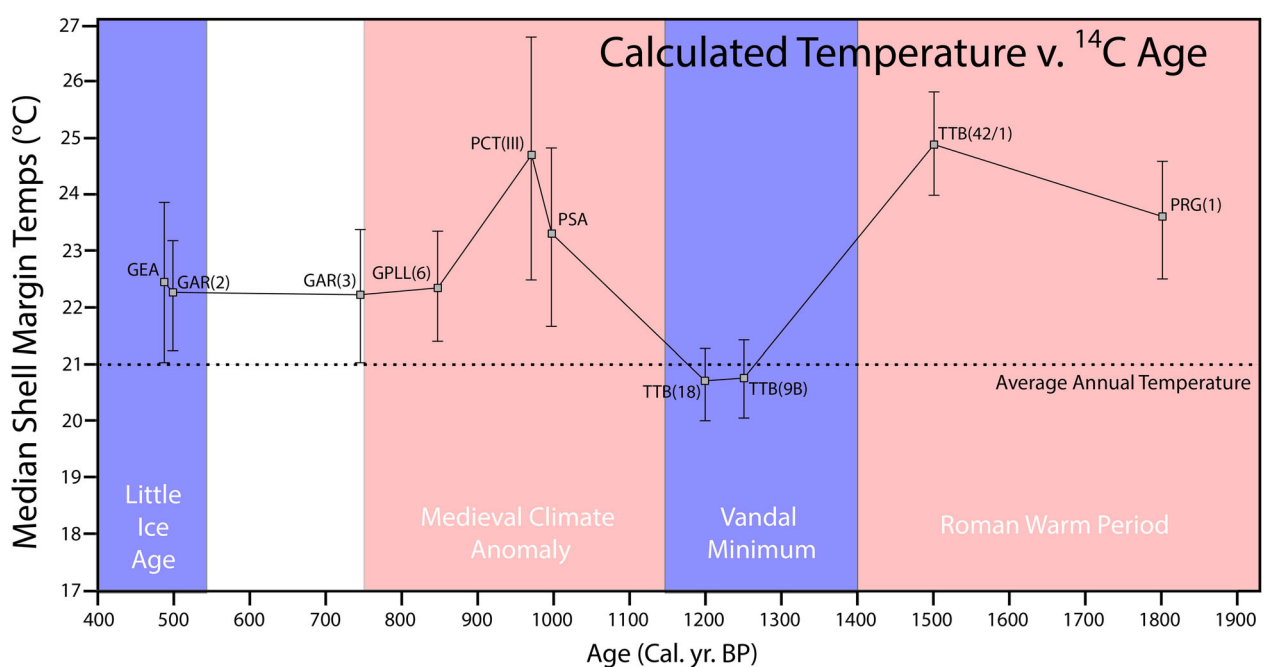


**Figure 6.** Box plot of maximum shell length (Y-axis) related to radiocarbon age (X-axis), including modern shells from Tenerife.

a year-round residence. These results contrast with those presented in this study of the Canary Islands. This inconsistency with other higher latitude sites suggests that local climate conditions and associated food production practices could result in differing human harvesting patterns.

Canarian shell midden sites (as opposed to residential middens), particularly those at Teno, Arguamul, El Águila, Puntallana, and Salamera, have been tentatively interpreted by local archaeologists to be sites of intensive harvests, where shells were likely collected and processed in a one-time or sporadic occurrence. It is proposed that the aboriginal population would collect the shells and extract the edible flesh on-site, then transport only the edible flesh inland to residential

sites, leaving behind the shells (Mesa Hernández 2006, 2008). This practice was common in other regions, including South Africa, because removing the edible material from the relatively bulky shells decreased the transportation cost of moving the food inland to residential sites (Langejans et al. 2012). The site at Grotto dell'Uzzo is not the site of intensive harvesting and processing, but rather one of ritualistic or episodic importance, indicating that the shells may not be indicative of the overall shellfishing patterns of the prehistoric population. This comparison between the Canary Islands and Grotto dell'Uzzo demonstrates that understanding how the prehistoric population utilised the site is critical to interpreting the information retrieved from zooarchaeological remains.



**Figure 7.** Median shell margin temperatures for each archaeological site compared to their calibrated radiocarbon ages. Coloured bands indicate abrupt climate events of the Northern Hemisphere.

**Table 5.** Mann–Whitney pairwise comparisons of median body sizes from the archaeological sites and the modern live-collected shells from Tenerife.

	Modern	TTB 9B	TTB 18	TTB 42/1	GAR 2	GAR 3	GEA	GPLL (6)	PCT (III)	PSA	PRG (1)
<b>Modern</b>											
TTB 9B	4.33E–05		0.002498	7.22E–06	7.44E–07	6.97E–07	2.15E–05	3.12E–07	0.04588	2.20E–05	2.93E–05
TTB 18	0.002498	0.01133		0.4727	0.004586	0.004586	0.531	0.0002461	0.02113	0.6776	0.6776
TTB 42/1	7.22E–06	0.01133	0.001706		0.0001827	0.0002461	0.03211	0.0001827	0.273	0.01726	0.004586
GAR 2	7.44E–07	0.004586	0.0001827	0.001706		0.03121	0.1985	0.0003298	0.01402	0.8501	0.6776
GAR 3	6.97E–07	0.004586	0.0001827	0.0002461	0.03121		0.007574	0.162	0.003611	0.03121	0.02113
GEA	2.15E–05	0.531	0.03211	0.1985	0.007574	0.007574		0.01402	0.004586	0.04515	0.0539
GPLL (6)	3.12E–07	0.0002461	0.0001827	0.0003298	0.007574	0.001736	0.001736		0.04431	0.4483	0.2225
PCT (III)	0.04588	0.02113	0.273	0.01402	0.003611	0.004586	0.0001498	0.001706		0.002202	0.004586
PSA	2.20E–05	0.6776	0.01726	0.8501	0.03121	0.04515	0.4483	0.002202	0.02575		0.02575
PRG (1)	2.93E–05	0.6776	0.004586	0.6776	0.02113	0.0539	0.2225	0.004586	0.02575	1	1

Notes: Light grey boxes show statistically significant comparisons (after Bonferroni correction). A total of 55 comparisons were conducted.

The relationship between site function and season of shellfish collection is supported by a study of Mesolithic sites in Scotland. In Fife, Scotland, growth line counting was used to determine the season of collection for the marine bivalve *Cerastoderma edule* Linnaeus, 1758 by Mesolithic Scottish groups (Deith 1983). In this study, Deith (1983) established that some human groups inhabited permanent or semi-permanent ‘residential bases’ from which they exploited a wide range of local resources, as well as more distant ‘field camps’ from which they exploited specialised resources and/or resources with a limited seasonal availability. About 75% of shells were collected in the winter months, with the remaining ~25% collected in the summer (Deith 1983). The field camps in Scotland seem to be particularly analogous to the shell middens of the Canary Islands. In Scotland, harsh winters would have inhibited agriculture and driven the prehistoric populations to gather marine resources to survive the winter. In the case of the Canary Islands, even though seasonal climate is milder than at higher latitudes, the hotter, drier summers may have played some role on the apparent intensification of shellfishing harvesting at SST > 21°C. In both cases, shellfishing likely occurred when other food resources became scarcer, and the shells were collected from a site that was farther away from the residential base of the population.

### Assessing Temporal Variations in Shellfishing Intensity

The results from limpet body-size analyses support two fundamental conclusions: (1) modern limpets are significantly smaller than those measured across archaeological sites and (2) most archaeological sites do not exhibit significant body-size differences when compared to each other (Table 5; Figure 6). Body sizes do not appear to correlate with the previously mentioned abrupt climate intervals (i.e. Roman Warm Period, Vandal Minimum, Medieval Climate Anomaly, Little Ice Age) from the Northern Hemisphere, suggesting that possible abrupt cooling and warming episodes during the late Holocene did not result in predictable changes in the limpet sizes.

The stark size difference between modern limpets and archaeological limpets suggest that, although the aboriginal populations of the Canary Islands may have impacted abundances and sizes of marine limpets over time, it is likely that the present-day anthropogenic impacts, including modern harvesting practices, are more intense than those of the recent past and exert a stronger impact on body sizes. It is unlikely that collection bias could account for these differences because the largest adult shells were preferentially collected in both the modern and archaeological settings, presenting a similar bias towards the largest shells. The largest shells would maximise the food that could be



extracted from limpets, and juvenile and small shells are generally discarded during harvesting practices. Therefore, it can be deduced that the largest modern shells are still significantly smaller than those recovered from archaeological sites.

In pristine environments, there are multiple factors that could impact shell sizes, including salinity, turbidity, water temperature, population density, predation, and human harvesting practices (Klein and Steele 2013). In this study, we propose that human harvesting practices are thought to be the primary factor driving body-size changes in the Canary Islands. This interpretation is based on the apparent lack of relationship between shell sizes and abrupt cooling and warming climate episodes of the Northern Hemisphere, and because other possible natural factors are not expected to have changed drastically over the last two millennia. However, we acknowledge that additional research and larger sample sizes are necessary to further test these hypotheses. The dramatic size reduction of modern shells measured here seems to suggest that human stressors have played a significant role.

A recent historical ecology study by Riera et al. (2016) measured body sizes of two *Patella* species (*P. candei* and *P. aspera*) as a proxy for anthropogenic pressure on the rocky intertidal ecosystems of Tenerife. This study found that in the two decades studied (1994–2014), the average maximum length of *P. aspera* decreased from ~30 to ~23 mm, and the average maximum length of *P. candei* decreased by 20%, from ~36 to ~31 mm. Our modern specimens collected in the Puertito de Güimar during 2011 and 2012 are slightly larger (~38 mm) than the average limpet size in Tenerife reported by Riera et al. (2016), which further reinforces that our sample collection was slightly biased towards the largest specimens, a bias also expected in the archaeological record. Riera et al. (2016) characterised the age structure of their assemblages, noting an abundance of juveniles and a distinct absence of older adult individuals, likely due to the preferential selection of larger adult individuals by human collectors. Riera et al. (2016) also note that, while shellfishing is officially regulated in the Canary Islands today (10 kg/person/day for professional harvesters and 3–5 kg/person/day for recreational harvesters), these regulations often go unenforced. Thus, there is no official record of the true volume of shellfish removed from the marine ecosystems near the Canary Islands, as a large portion of the shellfishing is conducted by individual citizens, not by professional or licensed harvesters. Riera et al. (2016) summarised these various findings and interpreted them as indictments of increasing harvesting practices, particularly illegal shellfishing, in the Canary Islands over the past two decades, and not as indicators of pollution or habitat destruction or as a result of other ecological/climatic mechanisms.

A previous study in the Canary Islands by Riera et al. (2014) focused on various threats to marine biodiversity in the Canary Islands, including pollution. Within the archipelago, the primary sources of pollution are point-source, and typically are restricted to fisheries, desalination plants, and thermal power plants, with small contributions from limited agriculture, and oil from urban runoff and ship traffic. The authors explain that, while there are quantifiable pollutants entering the ocean system in the Canary Islands, the persistent south-flowing currents quickly remove these from the near-shore ecosystems, and thus their impact seems negligible (Riera et al. 2014). Even considering that other human factors may have impacts on the body size of limpets in the Canary Islands, Riera et al. (2014) conclude that harvesting is still the major factor causing the reduced body sizes seen in the modern limpet populations. Comparison of these modern and archaeological shells, therefore, demonstrates that human harvesting practices have intensified from prehistoric times to the present and possibly are a primary causal factor in declining shellfish body sizes and populations. This is an ongoing and increasing pressure, as the modern population currently consumes *P. candei* as a significant dietary staple, and increasing population in the archipelago (up to ~2.3 million at present) should have influenced the body size decline and will likely continue to do so unless shellfishing strategies are monitored and regulated. The second hypothesis of this research seems to be supported by our data, but it is important to note that additional ecological, climatic and anthropogenic factors could have also contributed to the observed patterns (Riera et al. 2014).

The 10 archaeological sites studied here demonstrate little difference of limpet size among shell middens (Table 5; Figure 6). This finding indicates that the intensity of shellfish collection remained relatively constant between 1800 and 500 cal. yrs. BP because measured shellfish sizes did not decline significantly across either a temporal or spatial scale on the islands studied. However, larger sample sizes from these and other sites across the archipelago should further test this hypothesis.

As previously discussed, Teno Bajo is the site of more than 50 distinct shell middens, demonstrating that this was a 'field-camp' that was repeatedly visited by generations of native peoples (Mesa Hernández 2006, 2008). Therefore, the diminished shellfish sizes at Teno Bajo are likely representative of much larger population groups present on Tenerife than the other two islands. Cueva del Tendal also exhibits some smaller shells, including shells that are as small as modern ones, which may indicate prehistoric overfishing on the east coast of La Palma. However, the median value at Cueva del Tendal is still above the modern median, reinforcing the interpretation that modern

shells are significantly smaller than those in prehistoric shell middens.

### Intensity of Shellfishing Exploitation in Other Regions

Body size has been used to characterise exploitation patterns across various temporal scales and regions of the world, ranging from South Africa to California. All studies have drawn similar conclusions: anthropogenic overexploitation of marine resources (shellfish) will lead to a decline in body sizes over time. In South Africa, ongoing zooarchaeological research regarding human subsistence strategies utilise the marine limpets *Cymbula oculus* Born, 1778 and *Scutellastra argenvillei* Krauss, 1848, as well as the marine snail *Turbo sarmaticus* collected from African Middle and Late Stone Age sites in South Africa (Klein et al. 2004; Steele and Klein 2009; Klein and Steele 2013). They have determined that, while climatological conditions were similar between the Late Stone Age (present interglacial period of the Holocene) and Middle Stone Age (last interglacial period, 130–75 Ka), the shell sizes of the Late Stone Age sites were significantly smaller than their Middle Stone Age counterparts (Goñi 2007). Klein and Steele (2013) attributed this difference to the increase in human population from the Middle to Late Stone Ages, and the subsequent development of specialised equipment specifically for shellfishing to feed a larger population base.

A study by Langejans et al. (2012), encompassing many of the same sites in South Africa, sought to explore MSA subsistence strategies and resource intensification. In this study, they found that shellfish species composition changed through time at the archaeological sites (Langejans et al. 2012). At the same time, however, they noted a decrease in the overall weight of some high-yield species (such as the marine gastropod *T. sarmaticus* Linnaeus, 1758) over the course of the period of study (>115–57.9 Ka), indicating that the weight of available *T. sarmaticus* in the system also decreased (Langejans et al. 2012). The authors indicate that availability of robust, high-yield marine resources is easily depressed by overexploitation and used this to tentatively conclude that intensity of shellfish exploitation increased through the Middle Stone Age (Langejans et al. 2012). They do note, however, that the complex nature of the interrelationship between resource intensification, climate, prey choice, and collection methodology left them unable to unambiguously determine if population pressure was the driving factor in the observed changes in shellfish size and abundances (Langejans et al. 2012).

In the south of England, a study of body sizes and abundances of four marine gastropods, *Phorcus lineatus* da Costa, 1778, *Littorina littorea* Linnaeus, 1758, *Nucella lapillus* Linnaeus, 1758, and *Patella* spp.,

found that exploitation by humans changed the age structure of the marine community, in addition to depressing body sizes (Mannino and Thomas 2001). In this study of a Mesolithic site on the Isle of Portland, England, comparison of the minimum number of individuals (MNI) were conducted across multiple stratigraphic layers. In subsequent work, Thomas and Mannino (2017) note that raw MNI comparisons are potentially misleading, due to variations in the thicknesses of the targeted stratigraphic layers. The authors propose several solutions to their previously misleading counts, including (1) standardisation of MNIs with respect to stratigraphic layer thickness, (2) Quantification of shell weights, and (3) quantification of meat yields (Thomas and Mannino 2017). Through these analyses, it was determined that human exploitation of ontogenetically older shells prevented the community from having ‘old-age’ members (~7–8 years old or older). This truncates the age structure of the community, skewing subsequent harvests toward younger and younger organisms. They also present evidence that in these species, including organisms of the genus *Patella*, that body size is positively correlated to age, therefore supporting that a younger population is also a smaller one (Mannino and Thomas 2001). They also assess the relative abundances of the four shells present, and explain that limpets, like *Patella*, are often preferentially collected due to their high-yield and low-energy cost of processing; however, they are more difficult to collect from the rocky intertidal zone, and therefore are underrepresented in the assemblage, compared to *Phorcus* and *Littorina* (Mannino and Thomas 2001). In their 2017 paper, Mannino and Thomas reiterate that *Patella* was the favoured taxon, and likely contributed to a large portion of the historical human population’s diet, due to their very high meat yield relative to body size (Thomas and Mannino 2017). They also note that *Patella* is the first taxon studied to exhibit size truncation, likely in response to overfishing. Mannino and Thomas additionally address other environmental factors that may affect body sizes and abundances, including climate change. They rule out this explanation as the impact of climate change on *Phorcus* would have been greater than the other species studied, and this did not seem a reasonable explanation (Mannino and Thomas 2001). Moreover, if sea level had risen to levels similar to the present-day coastline, *Littorina* and *Phorcus*, which live in the upper intertidal zone, would have declined while *Patella*, which lives in the lower intertidal zone, would remain unaffected. If shoreline exposure to wave action had increased, *Patella* would have been unaffected or even increased in abundance compared to the others (Mannino and Thomas 2001). However, all species appear to have been affected in a relatively uniform manner, and thus Mannino and Thomas (2001) support that

harvesting practices and preferential selection of easily accessible and transportable shells are a plausible indicator of human population growth. In their subsequent work, the authors elaborate that the different taxa are preferentially target at different times in the stratigraphic record. *Patella* is targeted most in the earlier stratigraphic layers, while *Littorina* exploitation progressively increases throughout the stratigraphic sequence as other taxa become overexploited and fall away. In the end, all studied taxa exhibit a decline in body sizes that is likely a response to overfishing pressures (Thomas and Mannino 2017).

Studies measuring harvested marine resources by prehistoric and modern human groups consistently reveal the negative consequences of continued and increased overfishing and harvesting practices through time (Jackson et al. 2001). In their study detailing collapse of modern coastal ecosystems, Jackson et al. (2001) demonstrate that overfishing of shellfish, along with large invertebrates, was the first significant disturbance to all marine ecosystems that have subsequently collapsed. Overfishing in these ecosystems have resulted in increased turbidity, hypoxia or anoxia, benthic biodiversity losses, eutrophication, enhanced microbial production, increased prevalence of algal blooms, and increased the frequency of fish kills (Jackson et al. 2001). These negative consequences occur over generations, as these coastal ecosystems experience compounding anthropogenic pressures. Therefore, it is critical to understand the historical context around marine resource exploitation patterns to best illuminate past and present demands placed on modern coastal ecosystems and develop action plans to remediate these critical ecosystems. In our study, we have shown how the body size of harvested limpets in the Canary Islands was significantly larger during prehistoric times than today, and fosters the utility of archaeological records to assess long-term ecological consequences of coastal ecosystems exploited by humans.

## Conclusions

Shell margin  $\delta^{18}\text{O}$  values of archaeological *P. candei* were mostly harvested at warmer temperatures, with 75% reporting SSTs at or above 21°C. This supports the hypothesis that shellfishing practices were not conducted year-round. Instead, shellfishing appears to have been avoided during the coldest part of the year, which is supported by the absence of shells recording SSTs below 21°C in the studied sites. Although this dataset does not allow for detailed seasonal estimates, the results are conclusive and point to the absence of winter collection of shells in the western Canary Islands during aboriginal occupation.

Body sizes of the largest live-collected limpets were notably smaller than those found in the archaeological

record. Both modern and archaeological shells are expected to exhibit comparable sampling bias towards the largest shells and therefore, the observed differences in size seem to be realistic. There does not appear to be a significant relationship between body size and SST, which further supports human predation patterns as the primary driving factor influencing body size changes. This study adds to the growing scientific evidence that molluscan body sizes are inversely proportional to the intensity of human exploitation. This study also provides the first glimpse into how drastic human exploitation has been on the Canary Islands, which is still heavily reliant on marine resources.

Because the subsistence strategies of the aboriginal people from the Canary Islands are comparable to other Mediterranean cultures, this study provides a foundation for a broader regional archaeological perspective on the human-marine resource relationship in northwest Africa and the magnitude of changes in this relationship over time.

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