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Scale of time-averaging in archaeological shell middens from the Canary Islands

Wesley G Parker,[1] Yurena Yanes,[1] Eduardo Mesa Hernández,[2] Juan Carlos Hernández Marrero,[3] Jorge Pais[4] and Donna Surge[5]

Abstract

Characterizing the degree of disturbance in archaeological deposits is critically important for archaeologists assessing foraging strategies, environmental conditions, or behavior patterns of ancient human groups. Qualitative techniques (e.g. micromorphology analysis) have previously been applied to assess the degree of disturbance (age-mixing) in archaeological sites; however, quantitative dating of material in the sites provides a more robust assessment of potential age-mixing. Unfortunately, because of budget constraints, archaeologists are frequently forced to rely on few quantitative age dates for an assemblage, thus obfuscating the signal of age-mixing of the deposit. The development of an affordable and rapid carbonate-target accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dating method provides a cost-effective way to retrieve more quantitative dates from carbonate material in archaeological assemblages to assess the degree of age-mixing in the deposit. This study tests this new technique and dates numerous harvested marine limpet shells from archaeological sites in the Canary Islands to determine whether there is multidecadal to multicentennial age-mixing. A total of 58 shells retrieved from six sites and three islands yielded uncalibrated radiocarbon ages ranging from 2265 ± 40 to 765 ± 35 BP, coinciding with the time of prehistoric human occupation in these islands. While most shells from the same stratum showed statistically equivalent ages, in some cases we detected age ranges that exceeded the imprecisions from analytical errors. This investigation is one of the first to quantitatively illustrate that shells retrieved from depth intervals without evident stratigraphic disturbance do not always contain contemporaneous remains and, therefore, dating each specimen is valuable for developing further paleoclimatic and paleoanthropological inferences. This study presents the first report of carbonate-target ^{14}C ages from archaeological shell middens, and suggests that this novel radiocarbon methodology can be applied to these sites, thus allowing the generation of a more comprehensive chronology.

Keywords

age-mixing, Canary Islands, carbonate-target ^{14}C dating, Holocene, shell middens, time-averaging

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Introduction

Time-averaging or age-mixing of non-contemporaneous material in a single stratigraphic horizon can confound archaeological interpretations because material retrieved from time-averaged strata display the erroneous appearance of contemporaneity when they actually come from significantly different times (Armour-Chelu and Andrews, 1994; Holdaway and Wandsnider, 2006; Kidwell and Bosence, 1991; Kowalewski, 1996; New et al., 2019). The quantification of the scale (temporal span) of time-averaging has been a focus of attention in the paleontological community for decades because the degree of time-averaging impacts the scope of paleoclimatic and paleoecological inferences that can be drawn from fossil assemblages (e.g. Carroll et al., 2003; Kidwell, 1998; Kowalewski, 1996; Yanes et al., 2007). As a result, time-averaging has been intensively investigated across naturally accumulated Quaternary sedimentary settings, including coastal shellfish deposits, land snail accumulations, and mammal bone assemblages (e.g. Kidwell, 2002; Kidwell and Bosence, 1991; Kowalewski et al., 2017; Miller, 2011; New et al., 2019; Ritter et al., 2017; Terry and Novak, 2015; Yanes et al., 2007). These and many more studies cited therein have consistently shown that multi-centennial to multimillennial mixing may be expected for naturally occurring subfossil and fossil assemblages. In contrast, there appears to be a dearth of quantitative, peer-reviewed literature on the impacts that time-averaging has on interpretations and sampling methodologies employed by archaeologists, though qualitative methodologies (i.e. micromophology analyses) have been investigated as a means of determining the degree of disturbance in an archaeological deposit (e.g. Aldeias and Bicho, 2016; Balbo et al., 2010). It is critical to rectify this absence of quantitative data because time-averaging in archaeological assemblages can potentially bias the anthropological and environmental interpretations derived from them. Archaeological remains are often used to study paleoclimate dynamics, ancient human behavioral patterns, temporal shifts in ecological niches, and paleoenvironmental change (e.g. Andrus, 2011; Burchell et al., 2013b; Colonese et al., 2009; Langejans et al., 2012; Maca-Meyer et al., 2004; Mannino and

[1]University of Cincinnati, USA
[2]Universidad de La Laguna, Spain
[3]Museo Arqueológico de La Gomera (Cabildo Insular), Spain
[4]Museo Benehaorita de La Palma, Spain
[5]University of North Carolina at Chapel Hill, USA

Corresponding author:
Wesley G Parker, University of Cincinnati, 500 Geology-Physics Building, 345 Clifton Court, Cincinnati, OH 45221, USA.
Email: Parkerwg@mail.uc.edu

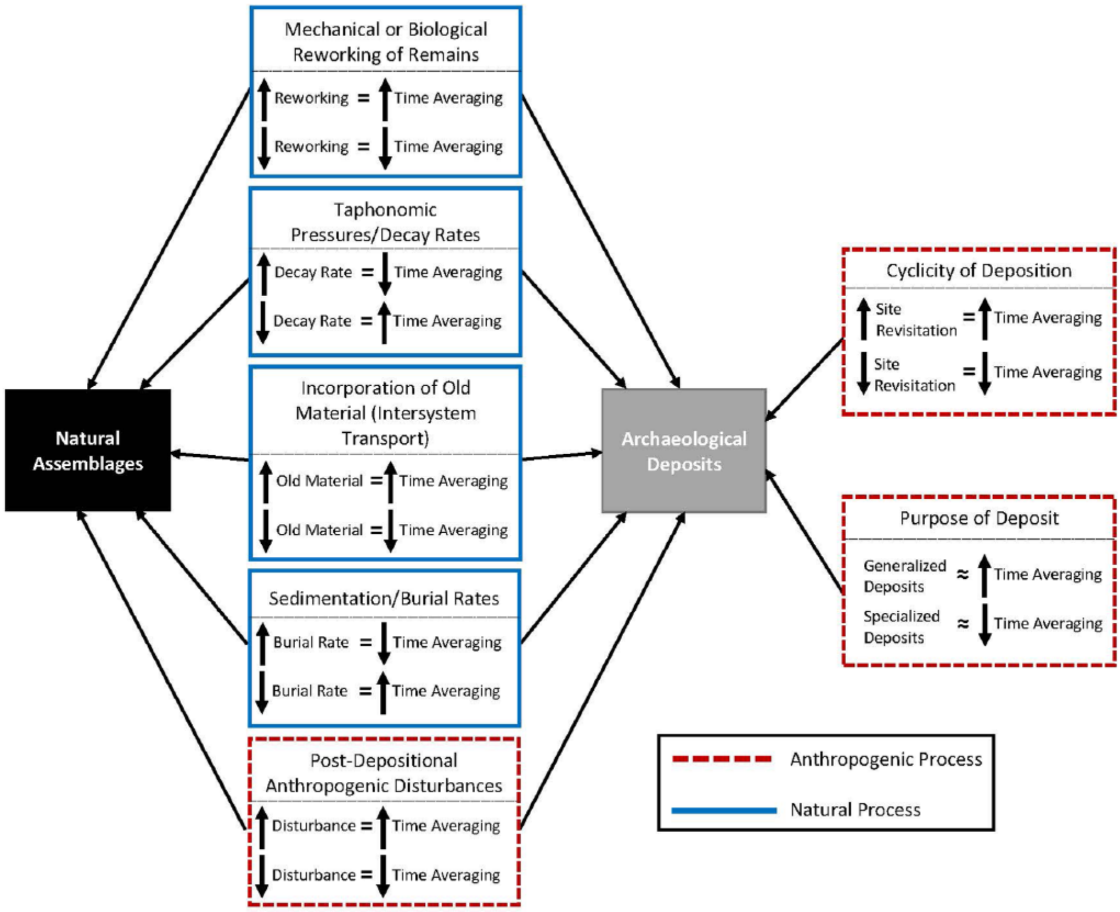

Figure 1. Visualization of the natural and anthropogenic processes that impact time-averaging in both natural (left) and archaeological (right) assemblages. Each box that originates arrow(s) contains a description of the process, as well as the specific impact it will have on the scale of time-averaging. Natural processes are denoted by blue, solid boxes; anthropogenic processes are denoted by red, dashed line boxes.

Thomas, 2001; Parker et al., 2018); yet natural and anthropogenic processes could significantly alter the temporal structure of these deposits, from single-use sites to multicentennial scale deposits, thus complicating interpretations drawn from these sites.

The scale and structure of time-averaging of a deposit, both natural and archaeological, result from the interplay of multiple biotic, abiotic, and anthropogenic processes (Figure 1). Within naturally occurring shellfish and bone deposits, time-averaging can be primarily impacted by (1) reworking and bioturbation of remains, (2) changes in sedimentation (burial) rates, (3) incorporation of material from older deposits, and (4) decay rates (taphonomic pressures) (Fürsch and Aberhan, 1990; Kidwell, 2002; Kidwell and Bosence, 1991; Kowalewski, 1996; Kowalewski et al., 1998; Olszewski, 2004). Archaeological assemblages are impacted by the same depositional and post-depositional processes as natural deposits but are also impacted by the manner in which ancient human groups acquired and discarded resources within the deposit. Additional factors impacting the scale and structure of time-averaging in archaeological assemblages include (1) seasonality, annual cyclicity, and scale of original material deposition (e.g. single-use sites vs multicentennial span inhabitations) and (2) the type of deposit (shell midden vs residential/kitchen midden) (Andrus, 2011; Bailey, 2007; Burchell et al., 2013a; Cannon and Burchell, 2017; Koppel et al., 2016; Schiffer, 1987). Naturally occurring and archaeological deposits are also both impacted by post-depositional cultural practices (e.g. resource recycling and reuse, or site reclamation, looting, or salvage) and are increasingly impacted by modern human activity, including ongoing urbanization, land-use changes, and deforestation (Holtz et al., 2014; Koppel et al., 2016; Olszewski, 2004; Schiffer, 1987; Williams and Corfield, 2003).

Analysis of the scale and structure of time-averaging is best accomplished through the dating of multiple materials collected from a focal stratum to assess and compare the temporal origins of each remain. While it is possible to infer significant time-averaging within Quaternary strata through qualitative/relative dating methodologies (e.g. comparison of ceramic stages or classification of local biotic invasions/extinctions), it is more objective to employ quantitative dating techniques combined with statistical analyses of variation and significance.

Two quantitative dating methodologies have commonly been applied to assess time-averaging in naturally occurring deposits: amino acid racemization (AAR) and radiocarbon dating. AAR is an analysis of the postmortem variance of the ratio between two mirrored orientations of amino acid chirality ('D' and 'L') in a deceased organism (e.g. Goodfriend, 1992; Kowalewski et al., 1998; Ritter et al., 2017; Yanes et al., 2007). However, because different AARs (shift from L to D) at different rates, this method must be calibrated using an independent age proxy such as radiocarbon dating (Goodfriend, 1992; Johnson and Miller, 1997). The rate of racemization is also temperature dependent, and thus, this methodology is not viable in material that has been exposed to extended periods of heat, such as shells or bone material discarded in a cookfire (Johnson and Miller, 1997). Therefore, archaeological studies intending to use AAR in shell middens must carefully screen for signs of remains that may have been exposed to fire. In contrast, a recent study by Lindauer et al. (2018) assessed radiocarbon ages from heated and nonheated shells and concluded that heating has no significant impact on the radiocarbon ages. Thus, radiocarbon dating is a more appropriate technique than AAR to date archaeological remains, because it is not sensitive to heat.

Radiocarbon (^{14}C) dating is the analysis of the relative abundance of the radioisotope ^{14}C in a carbon-bearing sample compared with the atmospheric abundance of ^{14}C through time. This analysis can be conducted using a variety of methodologies, including gas proportional counting, liquid scintillation, and accelerator mass spectrometry (AMS) (Bowman, 1990). Of these, AMS is considered to have the highest sensitivity and accuracy, and requires only 1 mg of material. AMS radiocarbon dating generates reproducibly reliable results and is often the preferred method for retrieving quantitative ages from Holocene deposits. Unfortunately, the preparation process for traditional 'graphite-target' samples can take several days, and the system is also costly to maintain. The expense of radiocarbon dating has historically precluded researchers from dating sufficient material to draw robust, statistically defensible conclusions about time-averaging in archaeological settings.

A recent publication by Bush et al. (2013), however, introduces a new method of sample preparation for AMS radiocarbon dating of carbonate materials that is approximately one-third of the cost of conventional graphite-target dating. This process loads carbonate directly into the test targets instead of converting them to graphite, thus reducing the processing cost and time of sample preparation, but introducing new uncertainty because of the increased probability of introducing impurities to the sample. In the published literature, this procedure is referred to as low-precision radiocarbon dating, carbonate-target radiocarbon dating, or rapid carbonate radiocarbon dating (Bush et al., 2013; Grothe et al., 2016; Kowalewski et al., 2017; New et al., 2019). Here, we refer to this process as carbonate-target dating per Kowalewski et al. (2017). The procedure is conducted at the University of California, Irvine, and has been shown to maintain high accuracy ($\pm 1.8\%$) for samples less than 10,000 years in age. This has been corroborated by several other studies (e.g. Dominguez et al., 2016; Kowalewski et al., 2017; New et al., 2019; Ritter et al., 2017) that have compared the results of both graphite-target (traditional) and carbonate-target AMS.

Use of the new carbonate-target radiocarbon method is becoming more common as the method continues to demonstrate reliability for a gamut of scientific studies that have also served to further constrain and validate the technique. To this end, studies have tested and validated the carbonate-target methodology for fossilized marine corals (e.g. Grothe et al., 2016; Hines et al., 2015), terrestrial gastropods (New et al., 2019), and natural molluscan death assemblages (Kowalewski et al., 2017; Ritter et al., 2017). It is possible, however, that some biogenic carbonates may be more amenable to carbonate-target radiocarbon dating, because of differences in organism physiology or feeding patterns, and thus ongoing research is being conducted to continue to calibrate and validate this method. The study of time-averaging has remained a predominantly paleontological preoccupation, and the recent development of the carbonate-target radiocarbon dating method provides a unique and cost-effective opportunity to expand the quantification of time-averaging into archaeological assemblages.

Within archaeology, the radiocarbon-based study of time-averaging is an evolution of the concept of time perspectivism, that is, the analysis of temporal and spatial relationships of archaeological data, initially discussed and later clarified by Bailey (1981, 2007). The concept arose from the recognition that cultural and physical processes produced palimpsests – homogenized units composed of previously separated material – that complicated critical analysis of archaeological deposits (Bailey, 2007; Koppel et al., 2016). Unfortunately, because of budget constraints, archaeologists are often unable to conduct more than one radiocarbon analysis per stratigraphic unit and are forced to rely on a handful of radiocarbon dates to constrain the temporal range of the entire site, thus limiting anthropological or climatological interpretations that can be retrieved from these sites (Koppel et al., 2016; Stein et al., 2003).

While any archaeological deposit can be impacted by the natural mechanisms of time-averaging, some sites – such as shell middens – are also particularly impacted by the depositional practices of human groups through time (Figure 1). Shell middens are large accumulations of shells, generated by prehistoric and historic groups that practiced shellfishing for gastronomic purposes, and are typically located in near-coastal environments including beaches, coastal bluffs, rock shelters, and so on (Andrus, 2011; Hallmann et al., 2013; Jerardino, 1998; Wurz, 2012). These deposits have been shown to vary widely in depositional frequency, from single-use to cyclic-use with recurrence intervals ranging from seasons to centuries, depending on the site and cultural background of the population that generated it (Andrus, 2011; Jerardino, 1997; Mannino and Thomas, 2001; Mannino et al., 2007; Mesa Hernández, 2006). Shell middens often exhibit high-quality preservation of remains because of shelter from destructive natural forces like wave and wind energy, and high pH soil levels that slow down the decay process (Andrus, 2011). Moreover, shell middens are powerful archaeological tools, as they can help scientists to reconstruct ancient human harvesting patterns, prey handling processes, taphonomic conditions, paleoecology and ecosystem health, paleoclimatic context, and so on (Andrus, 2011; Burchell et al., 2013a; Colonese et al., 2009; Hausmann and Meredith-Williams, 2017; Mannino et al., 2007; Parker et al., 2018; Prendergast et al., 2016). Interpretations of these physical data could be significantly strengthened if time-averaging was adequately constrained within these sites.

Here, we assess the scale of time-averaging within archaeological shell middens in a previously understudied but archaeologically rich subtropical Spanish archipelago, the Canary Islands. Shell middens from the Canary Islands provide a noteworthy challenge because of their limited chronological context. Previously dated localities are predominately concentrated in northwest Tenerife and northeast La Palma Islands (Mesa and Hernández, 2006, 2008; Soler Javaloyes et al., 2002). However, many other shell middens across the archipelago have been overlooked by the archaeological community and thus remain without robust chronological constraint. Most coastal shell middens in the Canary Islands are currently interpreted to be the sites of one-time harvesting cycles, and thus, researchers working in Canarian middens have traditionally dated one sample per midden and ascribed the resultant age to the entire deposit (Mesa Hernández, 2006, 2008). However, the scale of possible age-mixing in these deposits has not been assessed and, consequently, the presumption of constrained-time deposition has not been adequately tested. The timing of this research is also critical, because ongoing coastal development and sea-level rise threaten these coastal middens with imminent disappearance (Holtz et al., 2014). To rectify this knowledge gap, and preserve physical data before it is lost, the present research uses carbonate-target radiocarbon dating to examine whether shell middens from the western Canary Islands exhibit a significant scale of age-mixing beyond analytical error, by radiocarbon dating numerous mollusc shells retrieved from targeted shell middens across the western islands in the archipelago. The Canary Islands were selected for study because they hosted extensive aboriginal inhabitation prior to their annexation by the Spanish, and the aboriginal population was heavily reliant on rocky intertidal gastropods as a protein source (Mesa Hernández, 2006).

This investigation presents an unprecedented, more rigorous chronological approach to improve the study of shell middens that can be applied to their coastal and island settings across the world. This research also provides the first glimpse into the scale of time-averaging within archaeological shell middens in the Canary Islands, thus aiding future researchers to select appropriate sampling and radiocarbon dating techniques for their ongoing research into the climate, oceanography, ecology, and anthropology of the

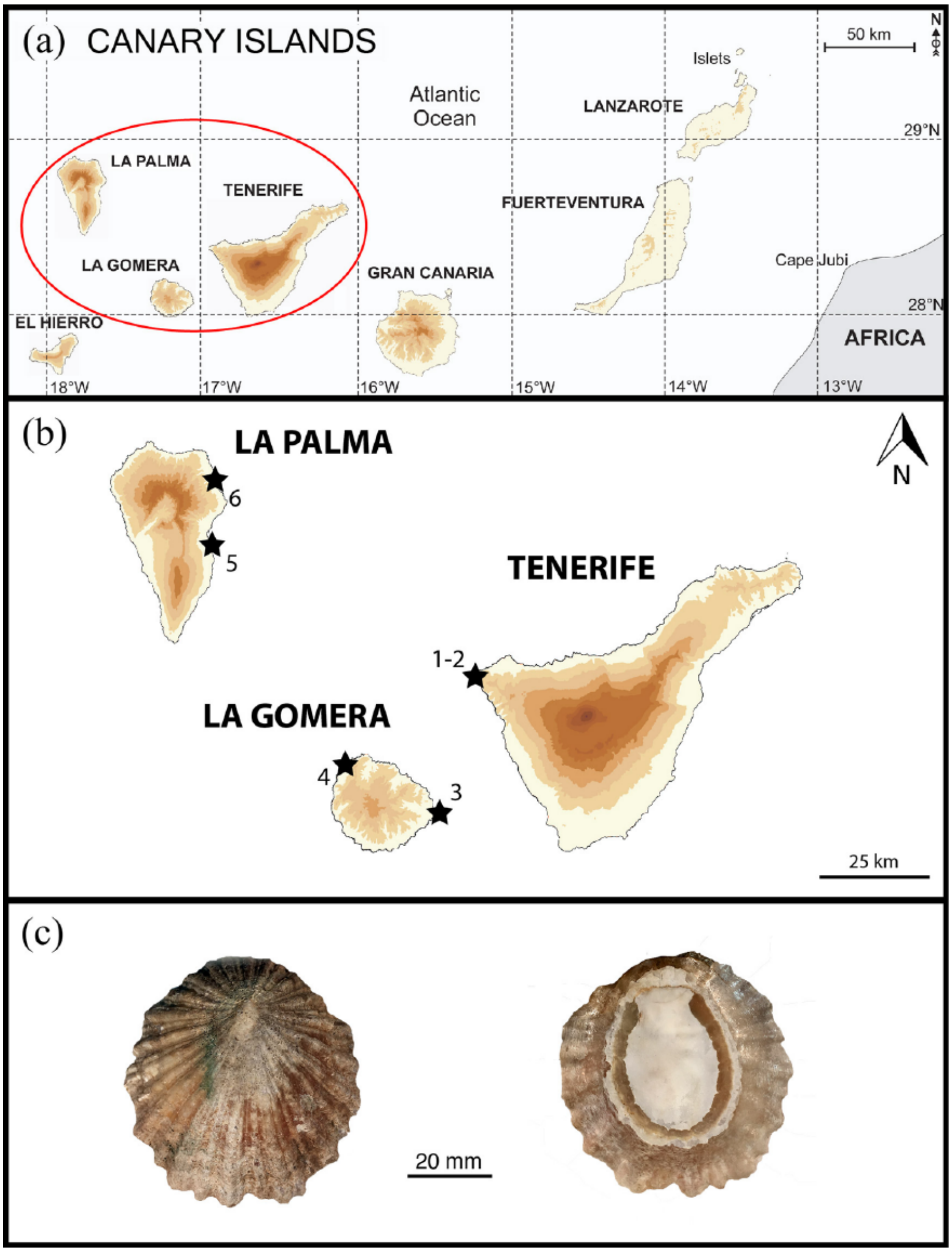

Figure 2. (a) The Canary Archipelago near the coast of Northwest Africa. Focal islands demarcated by the ellipse. (b) The focal islands with the locations of the archaeological sites numbered 1-2 (Teno Bajo), 3 (Puntallana), 4 (Arguamul), 5 (Roque de Los Guerra), and 6 (Cueva del Tendal). (c) Left: Dorsal view of *P. candei* shell (top = anterior, bottom = posterior). Right: Ventral view of P. candei shell (top = anterior, bottom = posterior).

Canary Archipelago and the greater Macaronesian and North Africa region.

Background information

Geographic and climatic context

The Canary Islands (latitude: 27°N–29°N; longitude: 13°W–18°W) are a volcanic, oceanic archipelago located in the Atlantic Ocean, off the coast of Morocco in North Africa (Figure 2a). The islands were formed by hotspot volcanism over the past 23 million years, and the underlying geologic structures are composed primarily of basaltic rocks (Van den Bogaard, 2013). The focal islands in this study, Tenerife, La Gomera, and La Palma, are located in the central and western side of the archipelago. The Canary Islands are located within the boundaries of the Northern Hemisphere subtropical high-pressure belt and are directly impacted by the poleward limits of the Hadley Cell. The archipelago is also located astride the Canary Current, an eastern boundary current that propagates parallel to the west coasts of Europe and North Africa, and is strongly influenced by the northwest African upwelling zone, which brings cold and nutrient-rich deep-ocean water to the surface along the West African coastline (García Herrera et al., 2001; Guimerans and Cañavate (1994); McGregor et al., 2007). Because of the confluence of climatic systems impacting the archipelago, the central and western islands broadly experience a Mediterranean climate with hot, dry summers and warm, wet winters (Sperling et al., 2004). As a result of the mild climate, ancient human groups were able to migrate from continental Africa and propagate across the archipelago, establishing distinct settlements and societies on each of the seven islands.

Archaeological context

At present, the Canary Islands are an autonomous region of Spain, but extensive aboriginal inhabitation in the archipelago began prior to European expansion, with the first North African settlers arriving by boat at approximately 2500 years BP (before present;

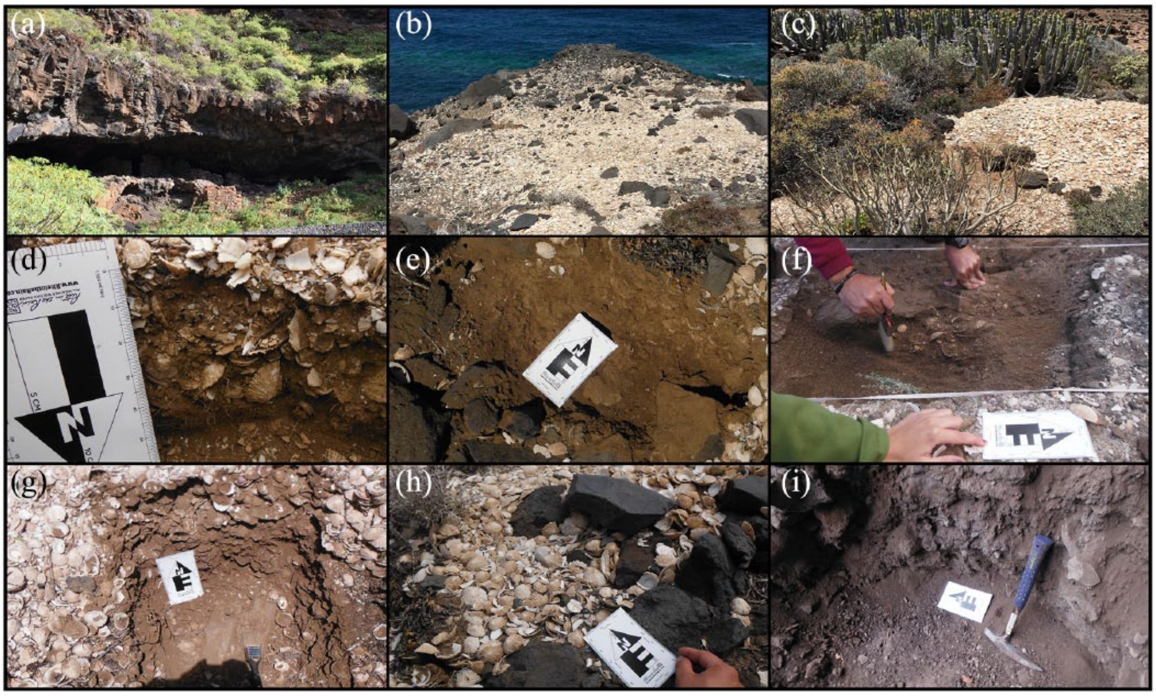

Figure 3. (a) The entrance to Cueva del Tendal on La Palma island. (b) A shell midden on a coastal cliff at Arguamul, La Gomera. (c) A shell midden on a coastal plain at Teno Bajo, Tenerife. (d–i) Photographs of Canary Island shell middens. The maximum length of the scale card arrow is 10 cm. (d) Teno Bajo 9B, Tenerife. (e) Excavated view of Arguamul 2, La Gomera. (f) Puntallana, La Gomera. (g) Teno Bajo 42, Tenerife. (h) Surface view of Arguamul 2, La Gomera. (i) Roque de Los Guerra, La Palma.

Fregel et al., 2009; Maca-Meyer et al., 2004). These settlers are descended from NW African Berbers, though mtDNA analysis also shows distant descent tracing back to Mediterranean Europe and Southwest Asia (Fregel et al., 2009; Maca-Meyer et al., 2004; Pinto et al., 1996; Rando et al., 1999). Genetic studies of the pre-Hispanic population in the archipelago support the local archaeological interpretation that there was little interisland migration during the period of aboriginal inhabitation, which is further evidenced by the distinct lack of seafaring vessels in the archaeological record (Maca-Meyer et al., 2004; Mercer, 1980).

The absence of significant interisland migration, compounded with the ecological and climatological differences across and between islands, resulted in a dramatic differentiation in cultures, agricultural practices, and hierarchical social systems among islands in the archipelago (Arnay-de-la-Rosa et al., 2009). Tenerife, the largest of the islands, had a robust agricultural system, though the diet of the population was strongly augmented by shellfishing and livestock (Arnay-de-la-Rosa et al., 2009, 2010). In contrast, La Gomera and La Palma both had moderate to small-scale horticulture, focusing primarily on barley cultivation, and were more reliant on livestock and hunter-gatherer subsistence strategies (Arnay-de-la-Rosa et al., 2009, 2010; Maca-Meyer et al., 2004). Across the archipelago, all aboriginal groups were heavily reliant on marine resources, including fish and shellfish, as evidenced by large shell middens throughout the coastal regions in the archipelago.

Shell middens in the Canary Islands are present on all inhabited islands in the archipelago, and are most often located within rock shelters, along coastal cliffs, or on beaches (Figure 3a–c) (Mesa Hernández, 2006). Canarian shell middens are composed primarily of shells from the genus *Patella Linnaeus*, 1758 (Gastropoda: Patellidae), including *Patella candei* d'Orbigny, 1840 and *Patella aspera* Röding, 1798 (Figure 2c). These organisms, known commonly as limpets, inhabit the rocky intertidal region of the near-shore environment and have been a critical protein source for the Canary Islands from antiquity to the present (Mesa Hernández, 2006; Parker et al., 2018). The taxonomy of several species of *Patella*, including *P. candei* used in this study, has been a topic of some contention. For this research we use the taxonomic name *P. candei*, following the World Register of Marine Species (Bouchet and Gofas, 2013; WoRMS Editorial Board, 2018). For additional details on the ecological background on *P. candei* see Parker et al. (2018).

Most coastal shell middens in the Canary Islands have no discernable stratigraphy. The lack of stratigraphic layering led to the general presumption that all material in a given shell midden was deposited as part of discrete shellfishing forays, and that sites were not revisited after initial use (Mesa Hernández, 2006). In addition to coastal shell middens, the Canary Islands have several residential (kitchen) middens (Soler Javaloyes et al., 2002). These were located close to aboriginal dwellings and are characterized by distinct stratigraphic layering that is interpreted to demonstrate continuous deposition over multiple generations. Residential middens contain charcoal, domesticated and wild animal bones, and pottery, in addition to marine mollusk shells. Both types of middens are dominated by *P. candei*, shells suitable for radiocarbon dating.

Materials and methods

Sampling methodology and site characteristics

Samples were freshly excavated from coastal middens by our research group in May 2016 with National Geographic Society funding support. Sites were selected based on accessibility and degree of preservation, as well as availability of historical and archaeological context. Shell samples of *P. candei* were excavated in situ under the supervision and direction of local collaborating archaeologists. All sites were classified as either shell middens or residential middens, depending on the composition and the presence of visible stratigraphy (Parker et al., 2018). In this research, shell middens are defined as shallow, coastal deposits dominated by patellid gastropods, while residential middens are defined as deeper, inland deposits that contain a mixture of

Table 1. Summary of the geographical and archaeological description of the studied shells middens from the western Canary Islands.

Island	Site name	Site Label	Elevation (m)	Depth (cm)	Latitude (°N)	Longitude (°W)	Type of deposit
Tenerife	Teno Bajo 9B	TTB 9B	26	9	28.35485	16.92206	Shell midden
Tenerife	Teno Bajo 42	TTB 42	63	43	28.36296	16.89895	Shell midden
La Gomera	Arguamul 2	GAR 2	25	43	28.20694	17.30123	Shell midden
La Gomera	Puntallana	GPLL	32	42	28.12859	17.1051	Shell midden
La Palma	Roque de Los Guerra	PRG	10	216	28.56745	17.76415	Residential midden
La Palma	Cueva del Tendal	PCT (III)	410	600	28.78679	17.76514	Residential midden

material including bones, pottery, charcoal, and shells. Shells collected from shell middens were collected in bulk, while shells retrieved from residential middens were collected at multiple depth intervals. Shells are labeled numerically in the order they were cleaned and processed. The characteristics of each site are summarized in Table 1. A map denoting the locations of the focal localities can be found in Figure 2a and b.

Sites on Tenerife were located in the northwest corner of the island in the Buenavista del Norte Archaeological Province, a region of the island well known for its abundant shell middens (Mesa Hernández, 2006). Two sites were analyzed from Tenerife, Teno Bajo 9B (Figure 3d) and Teno Bajo 42 (Figure 3g). No discernable stratigraphy was found at either site, leading both sites to be classified as shell middens. The shell midden at Teno Bajo 9B has a maximum depth of 9 cm, while the shell midden at Teno Bajo 42 has a maximum depth of 43 cm. Shells were collected across the entire depth range of both deposits.

Sites on La Gomera were located in two distinct provinces: Puntallana (southeast) and Arguamul (northwest). The site at Puntallana (Figure 3f) was classified as a shell midden and was determined to have a maximum depth of 42 cm. Collection from Puntallana was conducted across the entire depth range of the deposit. Three distinct shell middens in close proximity to each other can be found at Arguamul, in northwest La Gomera. Of these, Arguamul Site 2 (Figure 3e and h) was selected for radiocarbon dating because it had a high abundance of intact shells that can also be utilized in ongoing paleoclimatic and archaeological studies. Arguamul Site 2 has a maximum depth of 43 cm, and shells were collected across the entire depth range.

The final two sites are residential middens located on the eastern coast of La Palma Island, characterized by observable stratification. The first site, Roque de Los Guerra (Figure 3i), has a maximum depth of 216 cm. The midden was divided into five equal depth intervals, each approximately 40 cm in thickness. Only the lowermost level, Level 1 (160–195 cm), contained significant shell material, so sampling for radiocarbon analysis at this site was limited to Level 1. The second site on La Palma Island is the well-studied Cueva del Tendal site (Figure 3a), previously excavated in 1987. Archaeological artifacts were originally collected in stratigraphic order, and transported to the Museo Benehaorita de La Palma for curation and storage (Soler Javaloyes et al., 2002). The shells used in this study were retrieved from the museum collection, following proper curatorial practices. Shell material for this study was originally retrieved from quadrat S/4, depth interval XV, Area C of the Cueva del Tendal Site. This interval corresponds to ceramic phase IIIa, and this portion of the site had a total measured depth of ~600 cm (Soler Javaloyes et al., 2002). For further information on excavation procedures and definitions of specific stratigraphic units, see Soler Javaloyes et al. (2002).

Radiocarbon dating

For this study, 8 to 10 *P. candei* shells ($N = 58$) from each of the six selected sites were dated using the carbonate-target radiocarbon method. Five of these shells (from various sites) were selected for paired traditional graphite-target and carbonate-target dating, to test and verify the reliability of ages derived from the more novel carbonate-target dating approach. For these paired analyses, the same shells were analyzed using both the methods. Material was extracted from the shells using a Raytech 6" Diamond Impregnated Trim Saw. The whole shell is considered to be of the same age for the purpose of this research, as the lifespan of *P. candei* is well within the range of analytical uncertainty of both graphite-target and carbonate-target radiocarbon dating methodologies. All radiocarbon analyses were conducted via AMS at the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California-Irvine (UCI) following the standard procedures outlined in their laboratory protocols (https://www.ess.uci.edu/group/ams/protocols).

Samples slated for traditional graphite-target AMS were washed with deionized water to remove possible contaminants, and then leached in dilute HCl solution to remove possible secondary carbonate. Samples were then dissolved in 85% phosphoric acid in disposable septum-sealed reactors, producing CO_2 gas. The CO_2 was reduced to graphite using hydrogen and an Fe powder catalyst at 560°C (Culleton et al., 2006). The graphite was then pressed into the AMS target and analyzed by AMS.

For the carbonate-target procedure, 0.3 mg of shell material was ground into a fine powder, mixed with 5-mg unbaked Alfa Aesar #40510, −325 mesh, 99.99% pure Nb, and poured directly into the aluminum cathode target and pressed for AMS measurement (Bush et al., 2013). Material processed using this method does not undergo HCl leeching. Samples processed in this laboratory using traditional graphite-target methodology have exhibited 0.3% precision and 55,000-year backgrounds, while samples processed in the lab using carbonate-target methodology have been shown to have a precision statistically indistinguishable from the conventional method ($p > 0.05$) for samples less than 10,000 years old (https://www.ess.uci.edu/group/ams/facility/ams; Bush et al., 2013; Culleton et al., 2006).

The resultant radiocarbon ages (in years BP) were not calibrated to calendar years BP or BC/AD (Kowalewski et al., 2017), because the objective of this research is to quantitatively assess the scale of time-averaging within assemblages, which can be better accomplished without the additional uncertainty added by the conversion of radiocarbon ages to calendar ages.

Data analysis

A reduced major axis (RMA) regression line was produced from the comparison of the uncalibrated carbonate-target and graphite-target ages from the five *P. candei* shells that were dated using both methods. The RMA regression was selected in lieu of an ordinary least squares regression, because RMA regressions are better suited for datasets where both axes depict independent variables. This RMA line was then compared with a 1:1 line to assess the comparability of the results using the two methods. The scale of time-averaging within the assemblages was evaluated relative to the expected shell age variability attributed to uncertainty in the dating methodology. For uncalibrated radiocarbon ages, standard error was estimated empirically as ±40 years based on the combined imprecisions of the analytical analysis, as well as inter-shell and

Table 2. Comparison of carbonate-target and graphite-target ages generated from samples that were subjected to paired analyses.

Sample name	Carbonate-target		Graphite-target		Age difference	Comparison
	^{14}C age (BP)	±	^{14}C age (BP)	±	(Years)	(% difference)
GAR(2)-6	920	40	1015	15	−95	−9.4
GPLL6-1	1385	35	1435	15	−50	−3.5
TTB9B-1	1855	40	1815	15	40	2.2
TTB(42/1)-1	1980	35	2075	15	−95	−4.6
PRG1-1	2265	40	2335	15	−70	−3
Average					−54	−3.7

intra-shell variabilities. To determine whether standard deviations of the observed radiocarbon ages for a given sample were greater than what might be expected by chance, we employed simple Monte Carlo simulations for each sample (Yanes et al., 2007), conducted in the R statistical programming environment (R Core Team, 2013). In the simulation for a given sample, the same number of values as there are specimens in the actual sample (10 for all sites, except Arguamul 2, for which only 8 dated specimens were available) are first drawn at random from a normal distribution that has the same mean as the mean age of the actual sample, and a standard deviation set as the calculated analytical uncertainty of 40 years. The standard deviation of this randomly drawn sample is then determined, and the experiment is conducted a total of 10,000 times to generate a distribution of 10,000 standard deviations based on random sampling of the normal distribution. The 95th percentile value is then determined for the set of 10,000 standard deviations. If the actual standard deviation of the sample exceeds that of the aforementioned 95th percentile value, it can be said that the standard deviation of ages in the sample is greater than that expected by chance variation associated with the calibration error, and therefore, that there may be specimens of different ages in the sample.

Results

Comparison of graphite-target and carbonate radiocarbon methods

A comparison of uncalibrated carbonate-target and graphite-target ages can be found in Table 2. One shell from each of the following strata were dated using both methodologies: Puntallana, Arguamul 2, Teno Bajo 9B, Teno Bajo 42, and Roque de Los Guerra (Table 2). In four out of five the samples (80%), the carbonate-target ages underestimated the graphite-target ages by between −3% and −9.4%. At Teno Bajo 9B, however, carbonate-target data overestimate the graphite-target data by +2.2%. On average, the carbonate-target data underestimate the graphite-target data by −3.6%, which is larger than the ±1.8% offset calculated by Bush et al. (2013). In years BP, the offset between the two methods ranged from 40 to −95, with an average offset of −54 years. Analytical error ranges were also larger for carbonate-target dates than for graphite-target dates, with averages of ± 41 and ± 15, respectively. A statistical comparison of the RMA line derived from the comparison of carbonate- and graphite-target data to the 1:1 line, which depicts the perfect overlap between variables, demonstrated no statistical significance (p = 0.80). This indicates that, within error, carbonate-target data are strong indicator of the graphite-target data for the same shell (r^2 = 0.989; Figure 4). The slope of the RMA line is 0.983, while the intercept is +81.87 years BP.

Carbonate-target radiocarbon and Monte Carlo results

Uncalibrated radiocarbon ages and Monte Carlo simulation results are reported in Table 3. Age distribution histograms are presented in Figure 5. Ages are reported in years BP, where 0 BP = AD 1950. The oldest uncalibrated ages were retrieved from the residential midden at Roque de Los Guerra, La Palma Island. The youngest or most recent radiocarbon ages were retrieved from the shell midden at Arguamul Site 2, La Gomera Island. As noted earlier, standard deviations greater than the Monte Carlo generated 95th percentile standard deviation are considered significant, that is, age-mixing beyond uncertainty related to dating imprecisions.

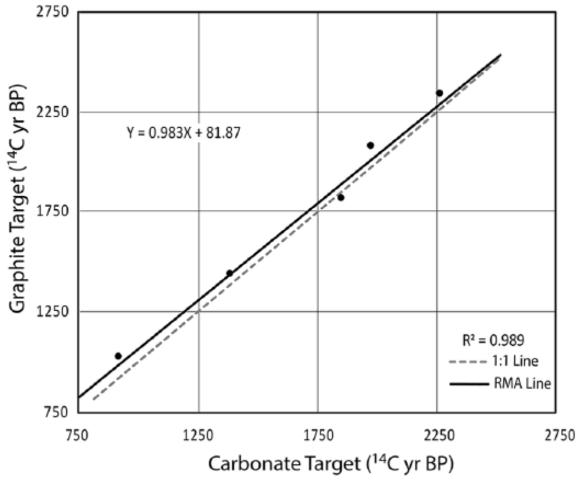

Figure 4. Comparison of uncalibrated graphite- and carbonate-target accelerator mass spectrometry (AMS) radiocarbon ages from the Canary Islands, Spain. The dashed gray line is representative of perfect agreement between the two AMS methods. The solid black line denotes the reduced major axis (RMA) regression line for the comparison of carbonate- and graphite-target AMS ages (slope = 0.944, intercept = 62.735). Analytical error for graphite-target ages (X-axis) is ±15 years BP. Analytical error for carbonate-target ages (Y-axis) is ±35–40 years BP. Note that there is no statistically significant difference between the RMA line and the 1:1 line (p = 0.80).

In the shell middens of Teno Bajo 9B, Arguamul Site 2, and Puntallana, the observed standard deviation of radiocarbon ages (±25 for TTB9B, ± 26 for GAR2, and ± 46 for GPLL) were all less than the Monte Carlo threshold, indicating that all three sites exhibit negligible age-mixing and therefore, they may be considered a single harvest, 'human-scale' event.

The residential middens at Roque de Los Guerra and Cueva del Tendal exhibited radiocarbon ages with a standard deviation of ± 117 and ± 66, respectively, thus exceeding the Monte Carlo threshold, suggesting that that the scale of age-mixing of these residential middens cannot be explained by dating imprecisions alone, and thus may be considered time-averaged.

The shell midden at Teno Bajo 42 also showed significant age standard deviations that exceed the threshold of analytical uncertainty. In this site, the standard deviation of the observed radiocarbon ages is ± 351 years. Therefore, this site could also be considered to be age-mixed. Even after the exclusion of the outlying age (765 BP), the standard deviation of the radiocarbon ages was ± 202, still exceeding the significance threshold.

Table 3. Uncalibrated carbonate-target AMS results, with sample mean, standard deviation (SD), and the Monte Carlo generated 95th percentile threshold for significance in SD. SDs in excess of the Monte Carlo generated 95th percentile threshold for significance are denoted as gray boxes.

Site name	Sample ID	^{14}C age (BP)	±	Sample mean	Sample SD	Monte Carlo 95th percentile
Puntallana (GPLL)	GPLL6-1	1385	35	1360	25	54.93
	GPLL6-2	1410	35			
	GPLL6-6	1370	45			
	GPLL6-8	1345	35			
	GPLL6-9	1380	35			
	GPLL3-1	1335	35			
	GPLL3-2	1355	45			
	GPLL3-3	1345	40			
	GPLL3-5	1335	40			
	GPLL3-6	1345	35			
Arguamul Site 2 (GAR2)	GAR2-1	885	35	893	26	56.84
	GAR2-2	890	45			
	GAR2-3	905	35			
	GAR2-5	845	35			
	GAR2-6	920	40			
	GAR2-7	870	35			
	GAR2-9	920	50			
	GAR2-10	910	45			
Roque de Los Guerra (PRG1)	PRG1-1	2265	40	2045	**117**	54.66
	PRG1-2	1980	40			
	PRG1-3	2090	40			
	PRG1-4	1905	35			
	PRG1-5	1980	35			
	PRG1-6	1945	40			
	PRG1-7	2005	40			
	PRG1-8	2200	60			
	PRG1-9	2110	40			
	PRG1-10	1970	35			
Teno Bajo 9B (TTB9B)	TTB9B-1	1855	40	1765	46	54.67
	TTB9B-1a	1760	60			
	TTB9B-2	1750	40			
	TTB9B-3	1680	70			
	TTB9B-4	1755	35			
	TTB9B-5	1800	40			
	TTB9B-7	1795	35			
	TTB9B-8	1770	45			
	TTB9B-9	1745	35			
	TTB9B-10	1740	60			
Teno Bajo 42 (TTB42)	TTB42/1-1	1980	35	1601	**351**	55.14
	TTB42/1-4	1870	40			
	TTB42/1-5	1830	35			
	TTB42/1-6	1865	40			
	TTB42/1-8	1690	45			
	TTB42/3-1	765	35			
	TTB42/3-2	1540	35			
	TTB42/3-5	1600	35			
	TTB42/3-11	1480	35			
	TTB42/3-13	1395	40			
Cueva del Tendal (PCT)	PCT-1	1695	35	1636	**66**	54.77
	PCT-2	1585	40			
	PCT-3	1575	40			
	PCT-4	1670	45			
	PCT-6	1670	45			
	PCT-9	1535	45			
	PCT-14	1730	45			
	PCT-16	1590	60			
	PCT-24	1605	45			
	PCT-29	1710	50			

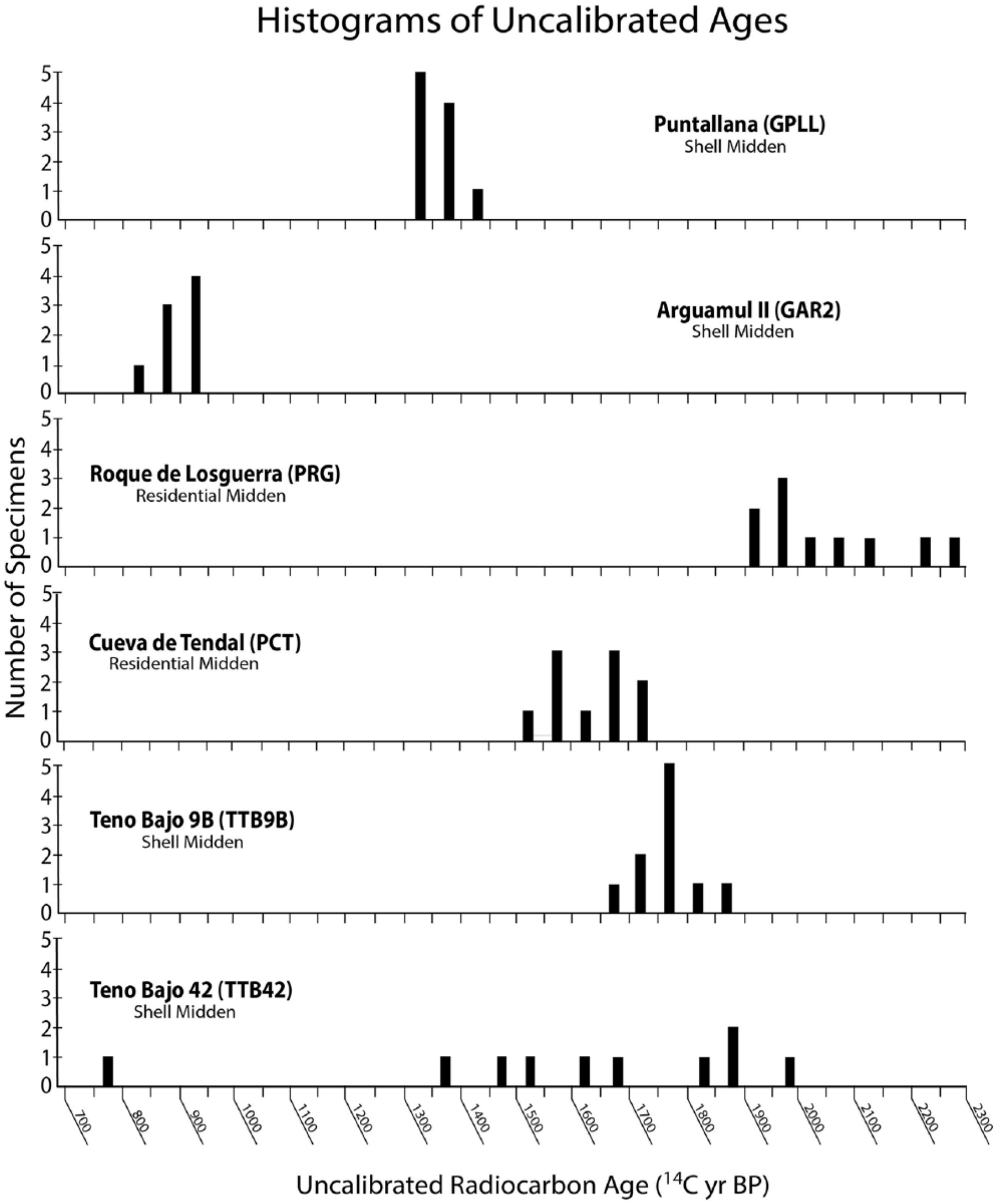

Figure 5. Age–frequency distribution histograms for uncalibrated carbonate-target radiocarbon ages of the mollusk *Patella candei* from archaeological shell middens. Bin size = 50 years.

Discussion

Graphite-target and carbonate-target radiocarbon methods

Our results suggest that carbonate-target AMS radiocarbon ages from shells of the marine limpet *P. candei* from archaeological sites in the Canary Islands yield ages statistically indistinguishable from those produced by the graphite-target AMS dating method, with an average offset of −54 years. Thus, the uncalibrated carbonate-target radiocarbon dating is a reliable predictor of uncalibrated graphite-target radiocarbon ages, as determined from the RMA line ($r^2 = 0.989$; Figure 4). This is virtually the same coefficient of determination ($r^2 = 0.99$) presented in Kowalewski et al. (2017), who were the first researchers to use carbonate-target radiocarbon ages to directly assess the scale of time-averaging of a natural calcium-carbonate skeletal assemblage.

Of the paired analyses in this study, four out of five resulted in carbonate-target ages that were lower than the graphite-target ages for the same samples. This is consistent with the results published in Bush et al. (2013) and Grothe et al. (2016), which found offsets ranging from −1.1% to −4.5%. The average percentage offset within ages from paired tests is −3.6%, which is larger than the average percentage difference reported in Bush et al. (2013), ±1.8%, but comparable to Grothe et al'.s (2016) findings. Nevertheless, the statistical indistinguishability of the carbonate- and graphite-target results indicates that the carbonate-target method is a reliable tool for assessing uncalibrated radiocarbon ages.

There are several sources of error that should be taken into consideration when interpreting these radiocarbon results. This includes error introduced by methodological differences in sample preparation between the graphite-target and carbonate-target methods. Samples processed using both graphite-target and carbonate-target methodologies were not pretreated in the same manner, as only graphite-target samples underwent 50% leeching with HCl immediately prior to hydrolysis. In addition, graphite-target samples were mixed with an Fe powder during the hydrolysis process, while the carbonate-target samples were mixed with niobium. This is because Fe has been shown to be the best transition metal to catalyze the graphitization reaction for graphite-target AMS measurement, but iron always contains some carbon, which increases the background and decreases the beam current in the carbonate-target method. Thus, the Antares AMS Lab in Australia proposed the switch to niobium as the preferred binder for the carbonate-target method. This difference in sample preparation methodology introduces potential error to the radiocarbon ages, and therefore calibration studies and rigorous testing of carbonate-target dates is still necessary to continue to validate the carbonate-target measurements.

An additional source of error is a possible taxon-specific offset between carbonate-target and graphite-target ages. While taxon-specific offsets have not been considered significant in the published literature, additional test of the fidelity of agreement between carbonate-target ages retrieved from different taxa in the same assemblage is a possible avenue for testing the reliability of carbonate-target ages. This is the subject of ongoing research.

A final potential source of error for radiocarbon dates (both graphite- and carbonate-target) acquired from *Patella* is the incorporation of 'dead' carbon (carbon containing no ^{14}C) into shell material (Ferguson et al., 2011). As *Patella* grazes, it dissolves home scars in the rocks. Thus, it is possible that ages of individuals may be affected by carbonate ingestion if the ingested carbon has a significantly different temporal origin from the shell. Comparisons of percentage of modern ^{14}C between archaeological and modern *Patella* shells in the Mediterranean have demonstrated offsets of 87–101%, which correspond to a possible age offset up to 1500 years (Ferguson et al., 2011). The incorporation of dead carbon into shells, however, is more common in carbonate platforms where grazing organisms have plentiful and abundant access to old carbonate material. In the Canary Islands the rocks in the intertidal region are predominately basaltic in composition, and accordingly, it is assumed that ingestion of old carbon is a negligible impacting factor on the ages retrieved from *P. candei* in this study.

Time-averaging in shell middens in the Canary Islands

The results presented in this study suggest that, while many of the analyzed shell middens in the Canary Islands do not appear to exhibit age-mixing, in some cases, the age dispersion seems greater than anticipated, supporting the hypothesis that the degree of age-mixing ranges from multidecadal to multicentennial in some instances. This was the case for the residential middens at Roque de Los Guerra and Cueva del Tendal, as well as the shell midden at Teno Bajo 42 (Table 3). At Roque de Los Guerra and Cueva del Tendal, this result is in accordance with our present understanding of how residential middens are generated in the Canary Islands. These middens are generated through the continuous deposition of shell, bone, charcoal, and ash across the span of multiple generations of human groups, and thus, it is reasonable to assume that any perturbation of the site could rework materials from significantly different ages. Therefore, archaeologists should take care to date multiple shells/artifacts when working with residential middens.

The remaining sites investigated here, however, are all shell middens that were presumed to have no age-mixing of non-contemporaneous shells. Yet, Teno Bajo 42 exhibits real time-averaging beyond the threshold of analytical uncertainty, which indicates that the archaeological presumption of one-time, discrete depositional events for all shell middens is not supported.

In all cases, the obtained distribution of shell dates is either uniform or exhibits a central tendency (Figure 5). The age distribution, or structure, of ages within a time-averaged deposit has been used within natural shellfish assemblages to assess both taphonomic durability of the target fauna as well as the taphonomic biases of the depositional setting (Flessa et al., 1993; Olszewski, 2004; Yanes et al., 2007). In previously studied natural assemblages, a right-skewed age distribution (larger number of younger shells) indicates a preservation bias against older material, while a left-skewed age distribution (larger number of older shells) indicates increased survivorship of older material, possibly because of changes in the environment or sampling deficiencies (e.g. Flessa et al., 1993; New et al., 2019; Yanes et al., 2007). While the number of shells dated in this study is too small to assess the structure of time-averaging, the central-tending or uniform structure of these deposits is a preliminary indicator that there is no significant taphonomic bias toward either younger or older shells. This hypothesis, however, remains to be tested in future research with increased sample sizes per midden.

It is important to note, as well, that adherence to the significance threshold (95th percentile Monte Carlo) could result in a type II error through the incorrect acceptance of the null hypothesis. It is possible that the aboriginal population revisited individual shell middens multiple times over a temporal span less than the significance threshold. Thus, middens might *not* be the sites of one-time depositional events, but rather are sites of repeated depositional events spanning a period of time that is below the significance threshold of this method. Additional study into the seasonality of shellfish collection could further inform this hypothesis, and is the subject of ongoing research (see Parker et al. (2018) for additional details). Regardless, these results support the view that most or all material retrieved from shell middens in the Canary Islands should be quantitatively dated, as it is possible that a quantitative date retrieved from one artifact (e.g. a shell) is not necessarily representative of the midden as a whole.

Radiocarbon dating and time-averaging in other locations

Radiocarbon dating has been used extensively to date material from archaeological sites, and to constrain the chronology and age range of material retrieved from these sites (e.g. Bicho et al., 2013; Nakamura et al., 2013). However, most of these studies do not include a rigorous assessment of time-averaging. The limited case studies of time-averaging from archaeological deposits elsewhere have primarily focused on bones and early hominid tools in Africa (Stern, 1994) and on the application of time-averaging to our understanding of foraging theory (Lyman, 2003) and cultural transmission (Madsen, 2012). Graphite-target radiocarbon dating of shells from shell middens has been used to quantify and constrain ages of material in the midden (e.g. Biagi, 1994), as well as to assess the fidelity and agreement between ages generated using multiple methods (Bateman et al., 2008), and even to assess periods of enhanced coastal upwelling (Latorre et al., 2017). The shells in this research are also derived from an upwelling zone, so the methods employed by Latorre et al. (2017) could be applied to material from archaeological deposits in the Canary Islands. This remains to be addressed in future research using the chronology developed in this study as the intellectual foundation. To date, we know of no published studies that have attempted to use graphite-target or carbonate-target radiocarbon dating to assess the scale of time-averaging in archaeological shell middens. AAR is, however, presently being investigated for expanded use in dating material from shell middens (Ortiz et al., 2018).

In addition, Koppel et al. (2016) used graphite-target radiocarbon calibrated AAR to assess time-averaging of shell middens. The authors investigated a midden in northern Western Australia that had a suite of charcoal- and bivalve-derived radiocarbon dates strongly suggesting that the midden was significantly time-averaged, and used AAR to examine the temporal parameters of the varying depositional units that comprised the larger midden (Koppel et al., 2016). Koppel et al. (2016) reported time-averaging on a multimillennial scale, which is greater than the multicentennial scale time-averaging reported in our research. While Koppel et al. (2016) does not use radiocarbon as the primary dating methodology through which they study time-averaging, and thus their research is not a direct analog to the research presented in this study, it does include several graphite-target radiocarbon dates that were used to initially establish the likely presence of significant time-averaging and calibrate the authors' AAR methodology.

Additional research using graphite-target radiocarbon dating in shell middens includes Bateman et al. (2008) and Latorre et al. (2017), which highlights the increased error associated with calibration of radiocarbon ages from shells that grew in upwelling zones. This error derives from the incorporation of carbon from rising deep water that has been separated from atmospheric mixing and is thus depleted in ^{14}C. The incorporation of this depleted ^{14}C into the shell is known as the reservoir effect (ΔR), causing anomalously depleted radiocarbon signals that must be mathematically corrected resulting in greater analytical uncertainty in the calibrated ages of the shells. However, this ΔR correction only needs to be applied if the objective of the research is to quantitatively assess calendar ages of the material. In the case of our study, the objective is to assess relative age differences between material, not determine exact calendar ages, and as a result, such calibration of the radiocarbon ages is not necessary, thus avoiding the error associated with ΔR corrections.

Finally, many investigations use non-shell material, such as bone (e.g. Biagi, 1994) and charcoal (e.g. Cann et al., 1991) to radiocarbon-date shell middens. Charcoal, in particular, is often present when other materials (ceramics, bones, tools, etc.) are not, and typically is a reliable secondary material that can be screened for radiocarbon ages. The dating of non-shell material was not performed as part of this study for several reasons. First and foremost, in most sites except Roque de Los Guerra, non-shell material is completely absent or exceedingly rare. In addition, the carbonate-target AMS methodology utilized for this research is only applicable to material that is naturally precipitated as calcium carbonate, and thus, materials such as bone or charcoal would require the more expensive graphite-target analysis for radiocarbon dating. Moreover, some non-shell material such as charcoal suffers from added sources of analytical or age uncertainty, including the 'old wood' phenomenon outlined in Blong and Gillespie (1978) and Schiffer (1986). Bone fragments and charcoal were retrieved from some sites, most notably Roque de Los Guerra, and are in storage at the University of Cincinnati. Ongoing, site-specific research is presently looking at the material from Roque de Los Guerra to assess the full temporal range and depositional patterns of the site. Across the archipelago, additional multiproxy, high-resolution studies need to be conducted to further constrain the true shellfishing patterns of the aboriginal population.

Conclusion

Limpet shell material of the species *P. candei* from six shell middens in the Canary Islands was analyzed to assess, for the first time, the scale and structure of time-averaging within archaeological layers. Numerous *P. candei* (n = 58) were dated using the new, rapid, and more affordable carbonate-target radiocarbon dating method.

Of the six middens, three horizons exhibited centennial-scale time-averaging beyond the limit of analytical uncertainty. The recognition of real time-averaging in a shell midden in the Canary Islands is in direct contrast to the prevailing presumption in the archipelago based on archaeological context alone, which presumes that all material in a shell midden was most likely contemporaneously deposited as part of discrete shellfishing events, and that sites were not revisited after abandonment. This research demonstrates that in some instances, real time-averaging beyond analytical error is documented in both residential and shell middens, which must be considered when studying shell middens in the region, as a date retrieved from a single shell may not be sufficiently representative of the age of the deposit as a whole. While in some case studies, coarse temporal resolution may be acceptable, in future paleoclimatic and paleoecological studies in the region, finer temporal resolutions may be attainable by dating many shells or materials within a horizon, as shown in this study.

The results of this study also indicate that uncalibrated radiocarbon ages generated using the carbonate-target AMS methodology, developed by Bush et al. (2013), are highly correlated with those generated by traditional graphite-target AMS dating. This agreement between the methods is in accordance with other studies and reveals that this method is applicable to archaeological *P. candei* shells from the Northwest Africa upwelling zone and other comparable settings.

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ORCID iD

Wesley G Parker https://orcid.org/0000-0002-9127-3762

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