IMPROVING THE ^{14}C DATING OF MARINE SHELLS FROM THE CANARY ISLANDS FOR CONSTRUCTING MORE RELIABLE AND ACCURATE CHRONOLOGIES

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ABSTRACT. Radiocarbon dating of closely associated marine mollusk shells and terrestrial material (charred wood or bone) collected from archaeological contexts on Tenerife and Fuerteventura islands allowed us to quantify the marine ^{14}C reservoir effect (ΔR) around the Canary Archipelago. Coastal Fuerteventura has a positive weighted mean ΔR value of +185 ± 30 ^{14}C yr, while for Tenerife a range of negative and positive values was obtained, resulting in a ΔR weighted mean value of 0 ± 35 ^{14}C yr. These values are in accordance with the hydrodynamic system present off the Canary Islands characterized by a coastal upwelling regime that affects the eastern islands (Fuerteventura and Lanzarote) but not the other islands of the archipelago, namely Tenerife. Because of this oceanographic pattern, we recommend the extrapolation of these results to the remaining islands of the archipelago, i.e. the first value must be used for the eastern islands, while for the central and western islands the acceptable ΔR value is 0 ± 35 ^{14}C yr.

INTRODUCTION

The assembly of chronologies based on marine shell radiocarbon dates can lead to several problems usually due to oceanographic factors. Background research into the oceanographic conditions as well as a quantification of the marine ^{14}C reservoir effect (ΔR) of the coastal area under investigation are essential in order to obtain reliable ^{14}C chronologies for that region using marine shell samples.

ΔR is defined as the difference between the reservoir age of the mixed layer of the regional ocean and the reservoir age of the mixed layer of the average world ocean in AD 1950 (Stuiver et al. 1986). The reservoir age, R(t), defined as the difference between conventional ^{14}C dates from a pair of coeval samples that lived in different carbon reservoirs, varies from region to region of the ocean (Stuiver et al. 1986; Stuiver and Braziunas 1993; Reimer et al. 2002; Reimer and Reimer 2006) since the oceanographic conditions present in each region are different due to the variability in water mass mixtures, wind regime, bathymetry, or upwelling of deep water. Positive (high) ΔR values can be correlated with a strong upwelling since upwelled waters are depleted in ^{14}C, while low or negative ΔR values correspond with a weak, or even nonexistent, upwelling. As a measure of the regional enhancement or depletion of ^{14}C, ΔR can also be used as an upwelling proxy, which provides the most direct signal of upwelling activity (Diffenbaugh et al. 2003).

This paper focuses on the Canary Archipelago, located in the North Atlantic Ocean between latitude 27–30°N and longitude 13–19°W. The archipelago comprises 7 islands of volcanic origin (Figure 1a). It can be divided into 3 groups: the eastern islands (Fuerteventura and Lanzarote); the central islands (Gran Canaria and Tenerife); and the western islands (La Palma, La Gomera, and El Hierro). Some islands are affected by the NW Africa coastal upwelling system, which is characterized by a complex and heterogeneous oceanographic pattern that extends south to Cape Verde in winter and north to the Iberian Peninsula in summer (Wooster et al. 1976; Láiz et al. 2000; Pelegrí et al. 2006). The dominant oceanic current is the Canary Current, which marks the eastern boundary of the North

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Atlantic Ocean subtropical gyre (Machín et al. 2006). This current results from 3 major constraints: i) the Azores Current; ii) the shape and bathymetry of the African continental shelf; and iii) the tradewinds (Figure 1b). By the joint action of these factors, the Azores Current flows west and reaches the African coast, turning south due to the shape and bathymetry of the African continental shelf and the tradewinds, forming the Canary Current (Machín et al. 2006; Pelegrí et al. 2005, 2006). Near Cape Blanc, the Canary Current separates from the African coast and flows west, forming the North Equatorial Current (Machín et al. 2006; Pelegrí et al. 2006).

The Canary Islands coastal waters can be divided into 4 areas with different oceanographic conditions (Figure 1a). The eastern islands (Fuerteventura and Lanzarote) are located in an area where the upwelling regime is present, while the remaining islands of the archipelago are located in a region where the influence of this hydrographic regime is absent.

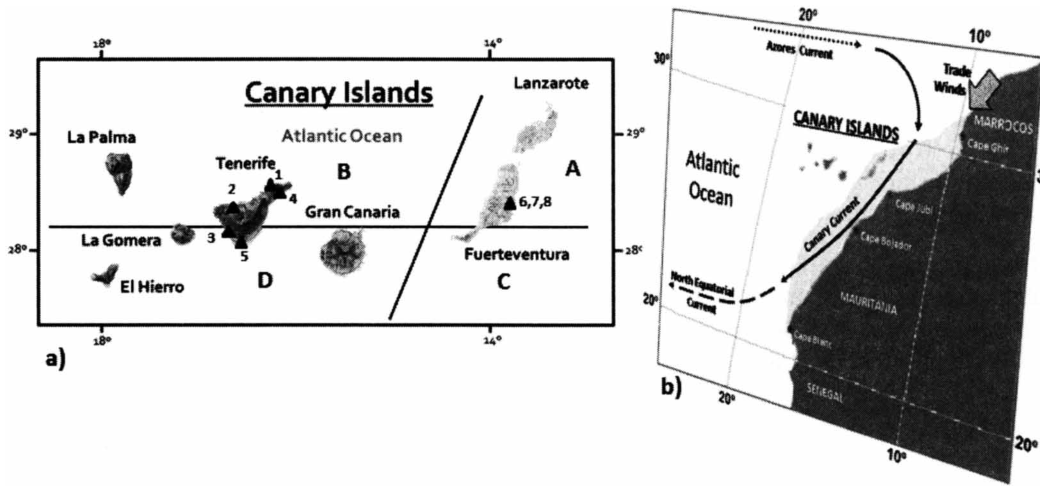

Figure 1 **a)** Location of the Canary Archipelago and upwelling transition zones present in its coastal waters following Barton et al. (1998): A – affected by the NW African coastal upwelling system; B – open ocean regime; C – affected by coastal upwelling and influenced by the islands; and D – oceanic regime disturbed by the island chain. Locations of the sampled archaeological sites: 1. Cueva de los Cabezazos; 2. Cueva de las Palomas; 3. Poblado de Palm-Mar; 4. Cueva de la Higuera Cota; 5. Salinas del Malpaís de Rasca; 6, 7, 8. Rosita del Vicario. **b)** Sketch of major constraints of the hydrodynamic system affecting the Canary Islands coastal waters.

Our study follows on from research undertaken by Soares et al. (2010) into ΔR values for Fuerteventura and Tenerife islands. Here, we present new ΔR values for these islands and also some examples of conversion of conventional ^{14}C dates of shell samples, collected in archaeological contexts at several Canarian islands, into calendar dates using these new data.

SAMPLING

Pairs of closely associated archaeological samples (marine shells/charred wood or bones) from each depositional context were collected from archaeological sites (Figure 1a) on Tenerife Island: 1. Cueva de los Cabezazos, Barranco de Agua de Dios (Tegueste); 2. Cueva de las Palomas (Icod); 3. Poblado de Palm-Mar (Arona); 4. Cueva de la Higuera Cota, Barranco de Agua de Dios (Tegueste); 5. Salinas del Malpaís de Rasca (Arona); and on Fuerteventura Island: 6,7,8. Rosita del Vicario, Barranco de la Torre (Antigua).

The samples come from domestic refuse thought to have accumulated rapidly, and due to the close proximity of sample collections for each pair, it is assumed that the deposition of both types of samples (terrestrial and marine) was simultaneous—in other words, that the time of death of the organisms from both reservoirs was the same. In addition, other samples of bones or shells were collected from the same level of the pair or from a different level in order to obtain not only a reliable chronology for the archaeological remains, but also to test the reliability of the ^{14}C dates determined with the sample pair.

EXPERIMENTAL AND DATA PROCESSING

Samples were first cleaned by manual removal of foreign material. Charred wood samples were further treated with acid/alkali/acid at 90 °C. Gelatin was extracted from bones samples (those with a N content >1% measured with an Elemental Analyzer 1110 (CHNS), CE Instruments) using the Longin method (Longin 1970). Marine shell samples were usually restricted to whole valves of the same species with no visual evidence of surface deterioration. Nevertheless, the outermost 30% by weight, at least, of the shells was discarded by controlled acid leaching (0.5M HCl at 25 °C). For some shell samples, a controlled acid hydrolysis was used to separate approximately equal sized volumes of CO_2 representative of the intermediate fraction and the inner fraction of the shells' carbonate structure, in order to be ^{14}C dated. Only the inner fraction ^{14}C date was considered in the calculation of ΔR and R(t), since the intermediate fraction is merely considered as an index of reliability for the inner fraction.

The ^{14}C content was measured by means of the liquid scintillation technique described in Soares (2005). All samples were converted to benzene and the ^{14}C content was measured in a Packard Tri-Carb 2770TR/SL spectrometer. Stable isotope enrichment values ($\delta^{13}C$) were determined for the CO_2 gas produced at the initial stage of benzene synthesis using a SIRA 10 (VG ISOGAS) isotope ratio mass spectrometer with a dual inlet. ^{14}C ages were calculated in accordance with the definitions recommended by Stuiver and Polach (1977).

ΔR AND R(T) CALCULATION

ΔR values were calculated converting the terrestrial biosphere sample ^{14}C age into a marine model age following Stuiver and Braziunas (1993) and Reimer et al. (2002). The terrestrial sample ^{14}C age was calibrated using the IntCal09 atmospheric calibration data set (Reimer et al. 2009) and subsequently, through the interpolation of the obtained calibrated interval (1σ) in the Marine09 calibration data set (Reimer et al. 2009), the marine model ^{14}C age $\pm 1\sigma$ was determined. This marine model age was then subtracted from the ^{14}C age of the associated marine shell sample to yield ΔR. The 1σ error for the ΔR determination is obtained by propagation of the errors on the marine age and the modeled marine age. The reservoir age, R(t), was also determined.

RESULTS AND DISCUSSION

^{14}C ages of the terrestrial/marine pairs collected in archaeological contexts from Tenerife and Fuerteventura islands are listed in Table 1. ΔR and R(t) values are also presented in the table. If the ΔR data are plotted against time (Figure 2), we can see that the Tenerife ΔR values are invariably lower than those from Fuerteventura. ΔR values range from –150 ± 100 to +60 ± 130 ^{14}C yr for Tenerife Island with a ΔR weighted mean value of 0 ± 35 ^{14}C yr. Regarding Fuerteventura Island, the ΔR values range from +150 ± 45 to +235 ± 50 ^{14}C yr with a ΔR weighted mean value of +185 ± 30 ^{14}C yr. A statistical criterion was established to determine if the ΔR value for a given pair fell within the limits established by the mathematical expression

$$A_R - A_m \leq 2\sqrt{\sigma_R^2 + \sigma_m^2}$$

where A_R is the median value for the given ΔR, σ_R^2 its associated variance, A_m the group mean, and σ_m^2 its associated variance. If the value falls outside the prescribed limits, it is rejected and a new weighted mean will be calculated. In our case, all the calculated ΔR values fall within the prescribed limits.

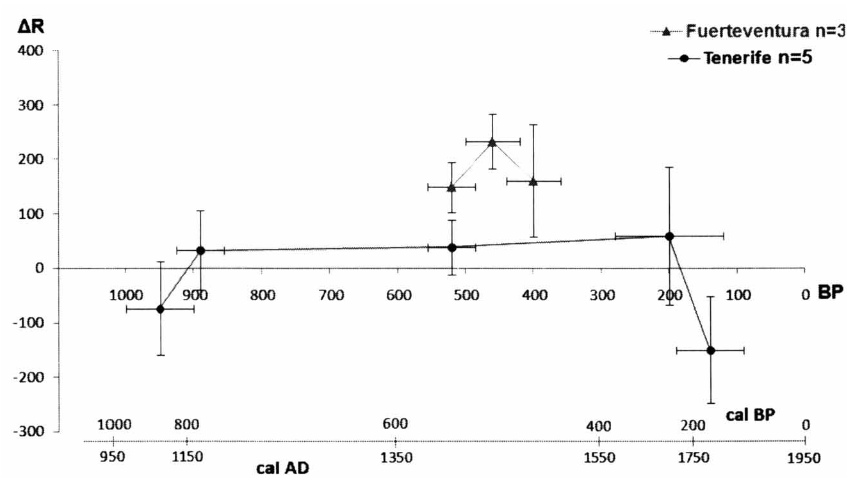

Figure 2 Marine ^{14}C reservoir effect off Fuerteventura and Tenerife islands. ΔR (±1σ) values are plotted versus terrestrial ^{14}C ages (±1σ).

It must be noted that it was not possible to undertake any prior anthracological analyses concerning the 2 charred wood samples collected at Cueva de la Higuera Cota and at Salinas del Malpaís de Rasca (see Table 1), both in Tenerife Island, in order to avoid the "old wood" effect problem that can lead to reduce the offset between marine and terrestrial ^{14}C ages used to calculate ΔR values. Nevertheless, the pair (Sac-2262; Sac-2251) gave the ΔR with the highest median value, while with the other pair (Sac-2258; Sac-2250) although the obtained ΔR has the lowest median value, it falls within the prescribed limits defined by the statistical criterion mentioned above. So, it seems that the old-wood effect does not exist in this case or at the most does not greatly affect the calculated ΔR weighted mean value for Tenerife Island.

As mentioned above, other samples, besides those included in the ΔR calculation, were collected for ^{14}C dating, namely from the archaeological sites of Rosita del Vicario and Cueva de las Palomas. The conventional ^{14}C ages obtained are presented in Table 2.

The site of Rosita del Vicario, on Fuerteventura Island, dates to the beginning of the Spanish conquest of the archipelago (AD 1402–1404) (Jiménez Sánchez 1965–1966). A shell sample (Sac-2588, 900 ± 35 BP) from the stratigraphic unit H19 (level IIB) is more recent than a shell sample from H18 (Sac-2581, 1140 ± 35 BP), and is also consistent with the shell dates from other strata of this site. A bone sample (Sac-2387) collected in a different sector (NE) seems to be an outlier since the sample age indicates a time before the conquest, i.e. cal AD 1180–1400 (2σ). Nevertheless, another shell sample of *Patella* sp. recovered at a superficial disturbed layer was ^{14}C dated and the value obtained 1560 ± 35 BP (Sac-2188), cal AD 910–1160 (2σ), suggests that an aboriginal occupation is also present at Rosita del Vicario.

Table 1 Marine ^{14}C reservoir effect values for coastal waters off Canary Archipelago.

Site name/lab nr	Shell sample description	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	Lab nr	Terrestrial sample description	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	Model marine ^{14}C age (yr BP)
Tenerife Island								
1) Cueva de los Cabezazos								
Sac-2255	*Patella* sp.	+2.10	1260 ± 60	Sac-2257	Animal bone	−20.86	950 ± 50	1334 ± 62
			ΔR = *−75 ± 85* ^{14}C *yr*				*R(t) = 310 ± 80* ^{14}C *yr*	
2) Cueva de las Palomas (Level 5)								
Sac-2603	*Patella* sp.	+0.19	1310 ± 35	Sac-2604	Animal bone	−21.26	890 ± 35	1277 ± 64
			ΔR = *35 ± 75* ^{14}C *yr*				*R(t) = 420 ± 50* ^{14}C *yr*	
3) Poblado de Palm-Mar								
Sac-2253[a]	*Patella* sp.	+2.40	890 ± 35					
Sac-2254	*Patella* sp.	+2.93	980 ± 40	Sac-2259	Animal bone	−19.26	520 ± 35	942 ± 36
			ΔR = *40 ± 50* ^{14}C *yr*				*R(t) = 460 ± 50* ^{14}C *yr*	
4) Cueva de la Higuera Cota								
Sac-2251	*Patella* sp.	+3.76	640 ± 60	Sac-2262	Charred wood	−24.30	200 ± 80	581 ± 112
			ΔR = *60 ± 130* ^{14}C *yr*				*R(t) = 440 ± 100* ^{14}C *yr*	
5) Salinas del Malpaís de Rasca								
Sac-2249[a]	*Patella* sp.	+1.46	370 ± 40					
Sac-2250	*Patella* sp.	+2.55	400 ± 40	Sac-2258	Charred wood	−22.90	140 ± 50	550 ± 90
			ΔR = *−150 ± 100* ^{14}C *yr*				*R(t) = 260 ± 65* ^{14}C *yr*	
Fuerteventura Island								
6) Rosita del Vicario (Level I) H016								
Sac-2415[a]	*Patella* sp.	+4.10	1170 ± 35					
Sac-2416	*Patella* sp.	+3.22	1090 ± 30	Sac-2389	Animal bone	−18.63	520 ± 35	942 ± 36
			ΔR = *150 ± 45* ^{14}C *yr*				*R(t) = 570 ± 45* ^{14}C *yr*	
7) Rosita del Vicario (Level IIb) H018								
Sac-2413[a]	*Patella* sp.	+2.65	1020 ± 35					
Sac-2414	*Patella* sp.	+2.91	970 ± 35	Sac-2388	Animal bone	−19.31	400 ± 40	811 ± 96
			ΔR = *160 ± 100* ^{14}C *yr*				*R(t) = 570 ± 50* ^{14}C *yr*	
8) Rosita del Vicario (Level IIB) H18								
Sac-2580[a]	*Patella* sp.	+1.36	1050 ± 35					
Sac-2581	*Patella* sp.	+1.73	1140 ± 35	Sac-2579	Animal bone	−19.20	460 ± 40	908 ± 36
			ΔR = *235 ± 50* ^{14}C *yr*				*R(t) = 680 ± 50* ^{14}C *yr*	

[a]Intermediate fraction (not considered in the calculation of ΔR and R(t)).

Table 2 ^{14}C age of samples collected at Rosita del Vicario and Cueva de las Palomas archaeological sites.

Site name / Lab nr	Sample ref. / Archaeological level	Shell sample description	$\delta^{13}C$ (‰)	^{14}C age (yr BP)
Rosita del Vicario				
Sac-2387	H019 / level II (NE)	Animal bone	–17.88	720 ± 60
Sac-2587[a]	H19 / level IIB	*Patella* sp.	+2.31	1060 ± 35
Sac-2588	H19 / level IIB	*Patella* sp.	+3.51	900 ± 35
Cueva de las Palomas				
Sac-2602	Level 4	*Patella* sp.	–0.41	1380 ± 35
Sac-2594	Level 3	*Patella* sp.	+0.27	1020 ± 35

[a]Intermediate fraction.

Cueva de las Palomas, one of the best documented archaeological sites on Tenerife Island, is related to the pre-Spanish occupation of this island, which took place around AD 1496 (Arco Aguilar and Atienzar Armas 1988; Arco Aguilar et al. 1997, 2000; Machado Yanes et al. 1997). Shell samples from 3 stratigraphic levels were ^{14}C dated as follows: level 5 (1310 ± 35 BP, Sac-2603); level 4 (1380 ± 35 BP, Sac-2602); and level 3 (1020 ± 35 BP, Sac-2594). These dates are in accordance with the stratigraphy and cultural context recorded at the archaeological site.

As mentioned above, positive high ΔR values can be correlated with a strong upwelling, while low or negative ΔR values correspond to a weak, or even nonexistent, upwelling. The values determined for coastal waters off Fuerteventura and Tenerife islands are in accordance with the hydrodynamic system present off the Canary Archipelago, which is characterized by a coastal upwelling regime that affects the eastern islands (Fuerteventura ΔR = +185 ± 30 ^{14}C yr) conversely to what happens off the other islands of the archipelago (Tenerife ΔR = 0 ± 35 ^{14}C yr), where the upwelling phenomenon does not prevail.

Similar values were already obtained for other coastal areas affected by the same upwelling system (the so-called NW Africa coastal upwelling system) namely: i) the Galician coast, ΔR values range from –280 ± 70 to +270 ± 40 ^{14}C yr, with negative values for the period 2500–900 BP, predominantly (Soares and Dias 2007); ii) the western Portuguese coast, ΔR weighted mean value of +95 ± 15 ^{14}C yr for the period 3000–600 BP (Soares and Dias 2006); iii) the southern Portuguese coast, western area, ΔR = +65 ± 20 ^{14}C yr; eastern area, ΔR = –65 ± 30 ^{14}C yr (Martins and Soares 2010; Soares and Martins 2010); iv) the Andalusian coast of Gulf of Cadiz, ΔR = –135 ± 20 ^{14}C yr (Soares and Martins 2010); v) northern Senegal, ΔR = +176 ± 15 ^{14}C yr (Ndeye 2008); vi) Mauritania, ΔR = +71 ± 13 ^{14}C yr (Ndeye 2008); and vii) Cape Verde Archipelago, ΔR = +70 ± 70 ^{14}C yr (Soares et al. 2011).

CANARY ISLANDS CHRONOLOGIES – SOME EXAMPLES

A set of marine ^{14}C dates was selected from 8 archaeological sites in the Canary Islands to test the ΔR values determined in this study. Calendar dates were calculated using the marine calibration curve Marine09 (Reimer et al. 2009) and the calibration program OxCal v 4.1 (Bronk Ramsey 2009). The results are presented in Table 3.

The archaeological site of Arguamul is located at Vallehermoso (La Gomera Island). Two shell middens, near the sea, were recorded at Arguamul: Arguamul 1 (western site) and Arguamul 2 (eastern site). The dated sample Sac-2174 was collected at Arguamul 1, and is associated with the pre-Spanish occupation of the island, which occurred in La Gomera during the 15th century. Two other post-conquest ^{14}C dates had been obtained for this site: CSIC-262, 280 ± 60 BP for Arguamul I (level II); and CSIC-263, 420 ± 60 BP for Arguamul II (level II).

The archaeological site of El Julan, located on Frontera (El Hierro Island), has the most important archaeological remains recorded on this island. The site includes an important set of rock engravings, combustion structures associated with animal sacrifice, and a possible meeting place called the Tagoror. Two large shell middens can be found on each side of this last structure. Archaeological excavations were undertaken in 1946 (Álvarez Delgado 1947), 1960 (Diego Cuscoy 1965), and 1976 (Hernández Pérez 2002). The calendar dates that were obtained are consistent with the stratigraphic sequence and are related to the aboriginal occupation of the site through the pre-Spanish occupation of the island.

Table 3 Calibrated data for selected archaeological sites in the Canary Islands.

Site name / Lab nr[a]	Shell sample description	^{14}C age (yr BP)	ΔR (^{14}C yr)	cal AD (2σ)
Arguamul 1(LG)				
Sac-2174 [1]	*Thais haemastoma*	940 ± 45	0 ± 35	1310–1490
CSIC-263 [2]	*Patella* sp.	420 ± 60	0 ± 35	1720–1950
CSIC-262 [2]	*Patella* sp.	280 ± 60	0 ± 35	1810–1950
El Julan (EH)				
VRI-777 [3]	unidentified	1010 ± 80	0 ± 35	1210–1490
VRI-778 [3]	unidentified	1140 ± 80	0 ± 35	1060–1410
VRI-779 [3]	unidentified	1260 ± 80	0 ± 35	970–1310
VRI-780 [3]	unidentified	1420 ± 80	0 ± 35	780–1180
VRI-791 [4]	unidentified	1820 ± 80	0 ± 35	380–750
La Restinga (EH)				
VRI-790 [4]	unidentified	790 ± 70	0 ± 35	1410–1680
La Restinga (GC)				
Gak-8056 [5]	unidentified	1030 ± 110	0 ± 35	1110–1520
Playa Aguadulce (GC)				
Beta-131030 [5]	unidentified	1930 ± 40	0 ± 35	330–610
Pozo Negro (FV)				
Sac-2240 [1]	*Thais haemastoma*	1130 ± 50	185 ± 30	1300–1490
Sac-2235 [1,b]	*Patella* sp.	1680 ± 35	—	—
Sac-2236 [1]	*Patella* sp.	1680 ± 35	185 ± 30	780–1020
Llano del Morrito (FV)				
Sac-2182 [1]	*Thais haemastoma*	640 ± 40	185 ± 30	1720–1950
El Rubicón (LZ)				
Sac-2179 [1]	*Thais haemastoma*	540 ± 50	185 ± 30	1770–1950

[a]Island abbreviations: (LG) – La Gomera; (EH) – El Hierro; (GC) – Gran Canaria; (FV) – Fuerteventura; (LZ) – Lanzarote.
[1] This study; [2] Acosta et al. 1975–1976; [3] Felber 1983; [4] Felber 1984; [5] Martín Rodríguez 2000.
[b]Intermediate fraction.

At the archaeological site La Restinga, also located on El Hierro Island, 2 shell middens, Punta del Salto I and II, can be found in the volcanic landscape. From Punta del Salto I, a shell sample was collected for ^{14}C dating. The calendar date, cal AD 1410–1680 (2σ), connects the dated archaeological content with a period after the Spanish conquest.

Shell samples from 2 archaeological sites at Gran Canaria Island, La Restinga and Playa de Aguadulce, were also ^{14}C dated. At La Restinga, located in a small promontory near the mouth of the stream Barranco de Telde, several structures were recorded: a defensive wall; several houses; and a grave. The calendar date, cal AD 1110–1520 (2σ), is related to an occupation level (II) of the site ascribed to the pre-conquest period. Playa de Aguadulce is an archaeological site located in a natural cave near the shoreline. The calendar date, cal AD 330–610 (2σ), also points to a pre-Spanish occupation of the site.

The archaeological site of Pozo Negro is located at Antigua (Fuerteventura). The dated samples were collected from a shell midden located near the mouth of the stream Barranco del Pozo Negro (Martín Socas et al. 1991, 1992). The calendar dates, cal AD 780–1020 and 1300–1490 (2σ), suggest 2 occupation events: the first one related to the pre-conquest period and the second one to the abandonment of the site about AD 1400, due to the Spanish conquest. Rosita del Vicario, dated to the beginning of the Spanish conquest of the archipelago (AD 1402–1404), as mentioned above, is located near this site.

Llano del Morrito, also located on Fuerteventura Island, not far from Rosita del Vicario, is an aboriginal site but where signs of the Spanish conquest are also present. The calendar date, cal AD 1720–1950 (2σ), can be associated with the post-conquest period that was identified on this site.

Finally, El Rubicón, located at Yaiza, in the eastern island of Lanzarote, is considered to be the first European settlement in the Canary Archipelago. The shell ^{14}C-dated sample was collected near a small church present at the site. The calendar date, cal AD 1770–1950 (2σ), is in accordance with the archaeological record.

CONCLUSIONS

ΔR values were determined for the coastal waters off 2 islands in the Canary Archipelago (Fuerteventura and Tenerife). ΔR has a positive weighted mean value of $+185 \pm 30$ ^{14}C yr for Fuerteventura, while for Tenerife a range of negative and positive values was obtained resulting in a ΔR weighted mean value of 0 ± 35 ^{14}C yr. These values are in accordance with the oceanographic pattern present in the Canary Archipelago, implying that the extrapolation of these results for the remaining islands of the archipelago seems reasonable, i.e. the first value must be used for the eastern islands, while for central and western islands the acceptable ΔR value is 0 ± 35 ^{14}C yr.

With these ΔR values and using the marine calibration curve (Marine09), accurate and reliable calendar dates should be obtained from shell samples collected on archaeological contexts in the Canary Islands. Nevertheless, further research using more pairs of preferably short-lived and identifiable samples not only from other islands of the archipelago, but also from these 2 islands—Tenerife and Fuerteventura—is needed, in order to measure more reliably the spatial and temporal variability of the marine ^{14}C reservoir effect in this North Atlantic region and to rule out or better evaluate the eventual influence of the old-wood effect in the quantification of the reservoir effect.

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