MARINE RADIOCARBON RESERVOIR EFFECT IN SOUTHERN ATLANTIC IBERIAN COAST

José M Matos Martins[1,2] • António M Monge Soares[1]

ABSTRACT. Research concerning the variability of the marine radiocarbon reservoir effect (ΔR) in the southern Iberian Atlantic coast confirms the existence of different ΔR values for regions that correspond to different oceanographic conditions. Due to these oceanographic conditions, the southern Iberian Atlantic coast can be divided into 3 zones: the Barlavento (windward), where the coastal waters are influenced by an intense upwelling of the northeastern Atlantic circulation (positive ΔR values); the Sotavento (leeward), where an upwelling area of minor intensity occurs; and the Andalusian coast, where because of its configuration does not present any wind-driven coastal upwelling (negative ΔR values). For the first time, ΔR values were determined for the Sotavento coastal region and, at the same time, new ΔR values were calculated for the Barlavento and the Andalusian coast for the last 3000 yr taking into account the data already obtained but now using a new methodology for calculation. In this way, ΔR weighted mean values were determined for the 3 regions of the southern Iberian Atlantic coast: ΔR = +69 ± 17 ^{14}C yr (Barlavento), ΔR = –26 ± 14 ^{14}C yr (Sotavento), and ΔR = –108 ± 31 ^{14}C yr (Andalusian coast). These values are in accordance with the different oceanographic conditions prevailing in these coastal regions. The data also allow identification of a Bond event at 0.8 ka cal BP and a drastic change in the oceanographic conditions in the Barlavento and Andalusian coastal areas during the 5th millennium cal BP.

INTRODUCTION

The marine radiocarbon reservoir effect (ΔR), 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), is often determined for a particular geographical region by ^{14}C dating pairs of samples of the same age but of different origin (terrestrial and marine). Although reservoir ages are time-dependent, ΔR is not. Nevertheless, complications can occur when rates of regional upwelling vary (Stuiver and Braziunas 1993:155). Since the intensity of ^{14}C depletion in the mixed layer depends upon the strength of wind-driven coastal upwelling and its rate is not constant but varies with time, it is likely that ΔR values can vary in the course of time in those regions (Kennett et al. 1997; Ingram 1998; Ascough et al. 2005; Soares 2005; Soares and Dias 2006a, 2007; Martins et al. 2012). High positive ΔR values can be correlated with a strong upwelling, 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 providing a significant direct signal of upwelling activity (Diffenbaugh et al. 2003).

Previous research concerning the variability of ΔR in coastal waters off Atlantic Iberia (Soares 1989, 1993, 2005, 2010; Soares and Dias 2006a,b, 2007; Soares and Martins 2009, 2010) allowed the quantification of ΔR, which is of crucial importance for the correct calibration of ^{14}C ages of marine samples. Moreover, the results have shown a good correlation between ΔR values and the oceanographic conditions present in the corresponding regions.

The western part of the southern Iberian Atlantic coast, the so-called Barlavento (windward) region, located between Cape San Vicente and Cape Santa Maria (Figure 1), is influenced by the dynamic effect of Cape San Vicente that allows upwelled water present along the western Portuguese coast to move southeastward and eastward, creating a quasi-permanent upwelling area around the cape

[1]Laboratório de Radiocarbono, Campus Tecnológico e Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Estrada Nacional 10, ao km 139,7, 2695-066 Bobadela LRS, Portugal.
[2]Faculdade de Ciências e Tecnologia, CIMA, Universidade do Algarve Campus de Gambelas, 8005-139 Faro, Portugal. Corresponding author. Email: jmartins@ctn.ist.utl.pt.

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(Fiúza 1982, 1983; Fiúza et al. 1982; Ferreira 1984). A ΔR weighted mean value of +65 ± 20 ^{14}C yr was determined in previous research for this coastal region, which is consistent with the prevailing oceanographic conditions (Soares and Martins 2009, 2010).

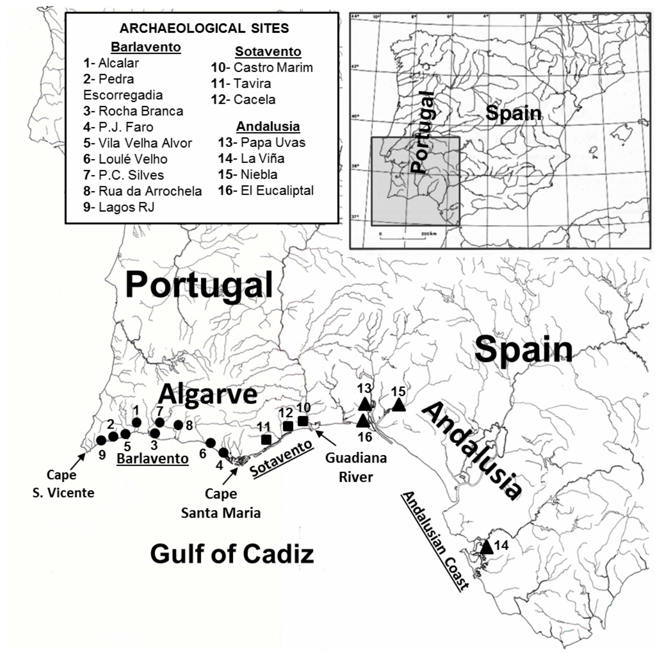

Figure 1 Location of coastal areas and archaeological sites analyzed herein

The central part of the southern Iberian Atlantic coast, the so-called Sotavento (leeward) region, located between Cape Santa Maria and the mouth of the Guadiana River (Figure 1), has not been analyzed in previous research concerning the variability of ΔR. In this region, when the prevailing winds in the Gulf of Cadiz are from the west, a minor upwelling area occurs offshore to the east of the cape (Vargas et al. 2003).

Finally, in the eastern part of the southern Iberian Atlantic coast (the Andalusian coast), due to its configuration (Figure 1) the wind-driven coastal upwelling is nonexistent. A ΔR weighted mean value of –135 ± 20 ^{14}C yr was determined in previous research, which is consistent with a nonexistent coastal upwelling, suggesting some stratification of the water column (Soares and Martins 2009, 2010). Thus, the Sotavento coastal region can be considered a transition zone between an area where upwelled waters are important due to the influence of the western coastal upwelling system and an area where the upwelling regime is absent.

The aim of this work is the quantification, for the first time, of ΔR for the Sotavento coastal region and the establishment of possible correlations between the ΔR values and the oceanographic conditions present in this region. A different methodology from that one applied in previous research was used in the calculation of the ΔR weighted mean values for the Barlavento and Andalusian coast, in order to corroborate and continue the previous research developed in this area of the southern Iberian Atlantic coast.

SAMPLING

Pairs of closely associated archaeological samples (marine shells/charred wood or bones) from each depositional context were collected from archaeological sites present in the Sotavento region (see Figure 1). Samples come from kitchen refuse thought to have accumulated rapidly. Due to the close proximity of the samples forming each pair, it is assumed that the deposition of both types of samples (terrestrial and marine) was simultaneous or, in other words, that the time of death of the organisms from both reservoirs was the same.

For charred wood samples collected at the Castro Marim and Tavira archaeological sites, it was possible to undertake an anthracological analysis prior to dating (see Table 1). Nevertheless, since the measurement of the sample activity was made using a conventional liquid scintillation counting (LSC), we need samples with a weight of several grams, which led to the use, with an exception, of long-lived vegetal remains instead of short-lived species. Whenever possible and in order to overcome this problem, we used bone samples from the same archaeological context, namely from Tavira (see Table 1). Also, a sample of long-lived vegetal species associated with an *Erica arborea* sample was dated for the same purpose.

Concerning the shell samples, we tried whenever possible to date different shell species in order to test not only if their respective ^{14}C dating results were influenced by dietary or habit preferences, but also to identify eventual outliers.

EXPERIMENTAL AND DATA PROCESSING

Analytical procedures are described in detail elsewhere (Soares 2005; Soares and Dias 2006a, 2007). ^{14}C ages were calculated in accordance with the definitions recommended by Stuiver and Polach (1977). ΔR values were calculated by converting the terrestrial biosphere sample ^{14}C age into a marine model age. This marine model age was then subtracted from the ^{14}C age of the associated marine shell sample to yield ΔR (Stuiver and Braziunas 1993; Reimer et al. 2002).

We used a methodology based on Ascough et al. (2005, 2007, 2009) and Russell et al. (2011) for calculating the ΔR values. As mentioned above, samples were ^{14}C dated using LSC, which leads to a reduced number of multiple paired samples from each archaeological context due to the large sample size needed for ^{14}C dating. This handicap made the fulfillment of the methodology proposed by those researchers impossible to follow for many of the dated contexts. Calculation of the ΔR values employed the following: a) unrounded ^{14}C ages; b) interpolation between calibration curves IntCal09 and Marine09 (Reimer el al. 2009) for converting the terrestrial biosphere sample ^{14}C age into a marine model age; c) chi-squared test ($\chi^2_{:0.05} = T$) as a statistical criterion in the definition of contemporary samples from each group (terrestrial or marine) collected in the same archaeological context (when more than 1 sample was available); and d) establishment of the set of ΔR values that can integrate the weighted mean calculation from each coastal region according to the chi-squared test ($\chi^2_{:0.05} = T$) results. The 1σ error for the ΔR determination is obtained by propagation of the errors on the marine age and the modeled marine age from each pair of samples.

We also determine the reservoir age, which is R(t) defined as the difference between conventional ^{14}C dates from a pair of coeval samples that lived in different carbon reservoirs (Stuiver et al. 1986).

Table 1 ^{14}C dates for Sotavento.

Lab code	Shell sample description	$\delta^{13}C$ (‰)	^{14}C age (BP)	Lab code	Terrestrial sample description	$\delta^{13}C$ (‰)	^{14}C age (BP)
10 - Castro Marim[1] (37°13′N; 7° 27′W)							
UE 340							
Sac-2443	*Cerastoderma edule*	–0.90	2755 ± 45	Sac-2444	Charcoal (*Fraxinus* sp. + *Olea europaea*)	–21.16	2458 ± 82
UE 345							
Sac-2446	*Donax trunculus*	0^b	2752 ± 37	Sac-2445	Charcoal (*O. europaea* + *Arbustus unedo* + *Pinus pinea* + *F. angustifolia*)	-25^b	2447 ± 83
UE 89							
Sac-2439	*Venerupis decussata*	–1.06	2636 ± 62	Sac-2441	Charcoal (*Erica arborea*)	–23.36	2474 ± 58
Sac-2438	*C. edule* + *V. decussata* + *Ensis siliqua*	0.72	2684 ± 37	Sac-2440	Charcoal (*O. europaea*)	–26.26	2419 ± 42
UE 215							
Sac-2448	*C. edule*	0^b	2740 ± 47	Sac-2449	Charcoal *(P. pinea)*	-25^b	2431 ± 55
UE 124							
Sac-2456	*C. edule*	–0.21	2669 ± 40	Sac-2458	Charcoal (*P. pinea* + *Quercus coccifera* + *O. europaea*)	–24.58	2427 ± 68
Sac-2457	*E. siliqua*	0^b	2636 ± 64				
UE 299							
Sac-2453	*C. edule* + *V. decussata*	0.31	2771 ± 60	Sac-2454	Charcoal (*P. pinea*)	–25.46	2419 ± 41
11 - Tavira (37°07′N; 7°39′W)							
RAF							
Sac-2496	*Murex trunculus*	–1.00	1984 ± 48	Sac-2497	Bones	–21.50	1662 ± 58
CSM							
				Sac-2470	Bones	–20.15	877 ± 51
Sac-2472	*C. edule*	–0.36	1133 ± 40	Sac-2498	Charcoal (*Ceratonia siliqua*)	–25.72	816 ± 41
Sap. 5							
Sac-2469	*V. decussata*	–2.63	1178 ± 37	Sac-2467	Bones	–22.56	708 ± 36
Sap. 6							
				Sac-2500	Charcoal *(Prunus* sp. + *P. avium/cerasus*)	–25.55	648 ± 39
Sac-2463	*C. edule*	–0.42	998 ± 42	Sac-2464	Bones	–21.58	651 ± 43
CNSP							
Sac-2462	*Murex brandaris*	0.62	699 ± 38	Sac-2460	Bones	–21.43	287 ± 36
Sac-2459	*Pecten maximus*	1.19	607 ± 34	Sac-2501	Charcoal (*Pistacea* sp. + *P. lentiscus*)	–24.47	251 ± 41

Table 1 ^{14}C dates for Sotavento. *(Continued)*

Lab code	Shell sample description	$\delta^{13}C$ (‰)	^{14}C age (BP)	Lab code	Terrestrial sample description	$\delta^{13}C$ (‰)	^{14}C age (BP)
12 - Cacela (37°10′N; 7° 32′W)							
UE 405							
Sac-2656	(several species)	0.61	1487 ± 44				
Sac-2655	*Charonia* sp.	0^b	1385 ± 55	Sac-2648	Bones	–20.50	866 ± 50
UE 410							
Sac-2679	*P. maximus*	0.45	1291 ± 35				
Sac-2682	*C. edule*	–0.19	1289 ± 47				
Sac-2675	*Venerupis decussata*	–1.04	1283 ± 64				
Sac-2677	*Solen marginatus*	–2.85	1203 ± 33	Sac-2649	Bones	–20.59	860 ± 36

[1]Arruda et al. (in press); [b]Not measured (estimated value).

Table 2 Results from each context of χ^2 tests for contemporaneity of ^{14}C dates concerning groups of terrestrial or marine samples.

Archaeological context	Marine samples	Terrestrial samples
Castro Marim (UE 89)	0.44; ($\chi^2_{:0.05} = 3.84$)	0.59; ($\chi^2_{:0.05} = 3.84$)
Castro Marim (UE 124)	0.19; ($\chi^2_{:0.05} = 3.84$)	—
Tavira (CSM)	—	0.87; ($\chi^2_{:0.05} = 3.84$)
Tavira (Sap.6)	—	0.00; ($\chi^2_{:0.05} = 3.84$)
Tavira (CNSP)	3.26; ($\chi^2_{:0.05} = 3.84$)	0.44; ($\chi^2_{:0.05} = 3.84$)
Cacela (UE 405)	2.10; ($\chi^2_{:0.05} = 3.84$)	—
Cacela (UE 410)	4.25; ($\chi^2_{:0.05} = 7.81$)	—

RESULTS AND DISCUSSION

^{14}C dates of the terrestrial/marine pairs collected in Sotavento archaeological contexts are listed in Table 1. The use of vegetal remains from long-lived species can lead to a reduced offset between marine and terrestrial ^{14}C ages of a pair, leading to an error in the calculation of the corresponding ΔR value. In the data in Table 1, there are 4 cases where besides the dating of a sample of long-lived species a sample of a short-lived species was also dated: Sac-2441, -2440 (Castro Marim UE 89); Sac-2470, -2498 (Tavira CSM); Sac-2500, -2464 (Tavira Sap. 6); Sac-2460, -2501 (Tavira CNSP). The dates determined for each pair are statistically indistinguishable (see Table 2). This leads us to consider that despite the fact that samples Sac-2440, -2498, -2500, and -2501 are from long-lived species, the presence of the "old wood effect" is negligible or insignificant, suggesting a good reliability for the ΔR values determined with these samples. In a first approach, therefore, the same can be applied to the data obtained with the other samples of long-lived species from Castro Marim.

For the archaeological contexts where more than 1 sample of the same origin (terrestrial or marine) was collected, a chi-squared test ($\chi^2_{:0.05} = T$) was performed. The results obtained with these tests are presented in Table 2, and show that the ^{14}C dates from each archaeological context are statistically indistinguishable, allowing the use of a multipaired sample approach for calculating the ΔR from these archaeological contexts.

The results using multi- and single-paired sample approaches are presented in Table 3. Tavira CNSP was one of the archaeological contexts with more samples from different origins (2 terrestrial, 2 marine). Four ΔR values were calculated, ranging from –108 ± 51 to +90 ± 90 ^{14}C yr, and, consequently, show some variability within the data set. The observed variability should not be ascribed to the nature of the marine biosphere samples but to ^{14}C dates obtained with the terrestrial biosphere samples (287 ± 36 and 251 ± 41 BP), which are encompassed in the last portion of the terrestrial calibration curve. The result is a multiplicity of ΔR values in the interpolation performed.

Table 3 Individual and ΔR weighted mean values from each archaeological context.

Archaeological context	Terrestrial sample ^{14}C age (BP)	Model marine ^{14}C age (BP)	Marine sample ^{14}C age (BP)	ΔR (^{14}C yr)	R(t) (^{14}C yr)
Castro Marim (UE 340)	2458 ± 82	2806 ± 104	2755 ± 45	**–51 ± 113**	297 ± 94
Castro Marim (UE 345)	2447 ± 83	2789 ± 90	2752 ± 37	**–37 ± 97**	305 ± 91
Castro Marim (UE 89)	2474 ± 58	2785 ± 55	2636 ± 62	–149 ± 83	162 ± 85
			2684 ± 37	–101 ± 66	210 ± 69
	2419 ± 42	2783 ± 80	2636 ± 62	–147 ± 101	217 ± 75
			2684 ± 37	–99 ± 88	265 ± 56
			ΔR weighted mean value = –120 ± 41 ^{14}C yr		
Castro Marim (UE 215)	2431 ± 55	2747 ± 45	2740 ± 47	**–7 ± 65**	309 ± 72
Castro Marim (UE 124)	2427 ± 68	2800 ± 101	2669 ± 40	–131 ± 109	242 ± 79
			2636 ± 64	–164 ± 120	209 ± 93
			ΔR weighted mean value = –146 ± 81 ^{14}C yr		
Castro Marim (UE 299)	2419 ± 41	2782 ± 79	2771 ± 60	**–11 ± 100**	352 ± 73
Tavira (RAF)	1662 ± 58	2028 ± 59	1984 ± 48	**–44 ± 76**	322 ± 75
Cacela (UE 405)	866 ± 50	1251 ± 50	1487 ± 44	+236 ± 67	621 ± 67
			1385 ± 55	+134 ± 74	519 ± 74
			ΔR weighted mean value = +190 ± 51 ^{14}C yr		
Cacela (UE 410)	860 ± 36	1234 ± 30	1291 ± 35	+57 ± 46	431 ± 50
			1289 ± 47	+55 ± 56	429 ± 59
			1283 ± 64	+49 ± 71	423 ± 73
			1203 ± 33	–31 ± 45	343 ± 49
			ΔR weighted mean value = +26 ± 26 ^{14}C yr		

Table 3 Individual and ΔR weighted mean values from each archaeological context. *(Continued)*

Archaeological context	Terrestrial sample ^{14}C age (BP)	Model marine ^{14}C age (BP)	Marine sample ^{14}C age (BP)	ΔR (^{14}C yr)	R(t) (^{14}C yr)
Tavira (CSM)	877 ± 51	1267 ± 63	1133 ± 40	–134 ± 75	256 ± 65
	816 ± 41	1188 ± 32	1133 ± 40	–55 ± 51	317 ± 57
			ΔR weighted mean value = –80 ± 42 ^{14}C yr		
Tavira (Sap.5)	708 ± 36	1123 ± 17	1178 ± 37	**+55 ± 41**	470 ± 52
Tavira (Sap.6)	648 ± 39	1056 ± 59	998 ± 42	–58 ± 72	350 ± 57
	651 ± 43	1058 ± 61	998 ± 42	–60 ± 74	347 ± 60
			ΔR weighted mean value = –59 ± 52 ^{14}C yr		
Tavira (CNSP)	287 ± 36	715 ± 38	699 ± 38	–16 ± 54	412 ± 52
			607 ± 34	–108 ± 51	320 ± 50
	251 ± 41	609 ± 82	699 ± 38	+90 ± 90	448 ± 56
			607 ± 34	–2 ± 89	356 ± 53
			ΔR weighted mean value = –37 ± 41 ^{14}C yr		

The data from previous research, namely from Barlavento and Andalusian coasts (Soares and Martins 2009, 2010) was recalculated according to the methodology mentioned above and used for the Sotavento coast. This approach was made in order to harmonize all the results for the southern Iberian Atlantic coast that are presented in Table 4. Calendar dates from each archaeological context were obtained using the respective conventional ^{14}C date (or weighted mean) determined with the terrestrial sample (or terrestrial samples), the calibration curve IntCal09 (Reimer et al. 2009) and the calibration program OxCal v 4.1 (Bronk Ramsey 2009).

Table 4 ΔR values for the 3 regions of the southern Iberian Atlantic coast (Barlavento, Sotavento, and Andalusia).

Archaeological context		^{14}C age (BP)	cal BC/AD (2σ)	cal BP (2σ)	ΔR (^{14}C yr)
Barlavento[1]					
Alcalar	M7	5636 ± 97	4710–4330 cal BC	6659–6279	+527 ± 54[a]
Pedra Escor.	—	3985 ± 55	2834–2300 cal BC	4783–4249	+553 ± 86[a]
Alcalar	[781]	3957 ± 45	2576–2306 cal BC	4525–4255	+158 ± 64
Rocha Branca	QD3	2566 ± 42	813–544 cal BC	2762–2493	+79 ± 73
Rocha Branca	QE3	2391 ± 44	750–389 cal BC	2699–2338	+158 ± 58
P.J. Faro	EA	2234 ± 40	390–203 cal BC	2339–2152	+40 ± 74
V.V. Alvor	—	2105 ± 65	359 cal BC–24 cal AD	2308–1927	+36 ± 110
Loulé Velho	Abside	2028 ± 72	345 cal BC–128 cal AD	2294–1823	+113 ± 87
Loulé Velho	2	1754 ± 44	138–392 cal AD	1812–1558	+32 ± 62
P.C. Silves	Q30	1277 ± 38	659–861 cal AD	1292–1090	–51 ± 64
P.C. Silves	Q4	1139 ± 45	776–992 cal AD	1174–959	+380 ± 75[a]
R. Arrochela	Silo 4	1060 ± 41	891–1029 cal AD	1060–921	+67 ± 35
Lagos	RJ306	564 ± 36	1302–1430 cal AD	648–520	+59 ± 55
Lagos	RJ37	539 ± 34	1312–1440 cal AD	638–511	+77 ± 47
Lagos	RJ86	423 ± 35	1419–1620 cal AD	531–330	+106 ± 49
Modern			—	—	+353 ± 85[a]
Weighted mean calculation		$\chi^2_{:0.05} = T$ (**1st test**) 127.25; ($\chi^2_{:0.05}$ = 23.68) $\chi^2_{:0.05} = T$ (**2nd test**) 9.32; ($\chi^2_{:0.05}$ = 19.68)			[a]rejected values
Weighted mean: **+ 69 ± 17 ^{14}C yr**					
Sotavento					
Castro Marim	UE 340	2458 ± 82	782–402 cal BC	2731–2351	–51 ± 113
Castro Marim	UE 345	2447 ± 83	780–398 cal BC	2729–2347	–37 ± 97
Castro Marim	UE 89	2438 ± 34	752–406 cal BC	2701–2355	–120 ± 41
Castro Marim	UE 215	2431 ± 55	757–401 cal BC	2706–2350	–7 ± 65
Castro Marim	UE 124	2427 ± 68	764–397 cal BC	2713–2346	–146 ± 81

Table 4 ΔR values for the 3 regions of the southern Iberian Atlantic coast (Barlavento, Sotavento, and Andalusia). *(Continued)*

Archaeological context		^{14}C age (BP)	cal BC/AD (2σ)	cal BP (2σ)	ΔR (^{14}C yr)
Castro Marim	UE 299	2419 ± 41	752–399 cal BC	2701–2348	–11 ± 100
Tavira	RAF	1662 ± 58	252–536 cal AD	1669–1415	–44 ± 76
Cacela	UE 405	866 ± 50	1040–1260 cal AD	910–690	+190 ± 51[b]
Cacela	UE 410	860 ± 36	1046–1260 cal AD	905–690	+26 ± 26
Tavira	CSM	839 ± 32	1057–1265 cal AD	893–685	–80 ± 42
Tavira	Sap.5	708 ± 36	1227–1389 cal AD	723–562	+55 ± 41
Tavira	Sap.6	649 ± 29	1281–1395 cal AD	670–556	–59 ± 52
Tavira	CNSP	271 ± 27	1520–1797 cal AD	430–153	–37 ± 32
Modern			—	—	+17 ± 52
Weighted mean calculation		$\chi^2_{:0.05}$ = *T* (**1st test**) 34.59; ($\chi^2_{:0.05}$ = 21.03)			[b]rejected value
		$\chi^2_{:0.05}$ = *T* (**2nd test**) 17.75; ($\chi^2_{:0.05}$ = 19.68)			
Weighted mean: **–26 ± 14 ^{14}C yr**					
Andalusian coast[1]					
Papa Uvas	E15	4574 ± 108	3632–2942 cal BC	5581–4891	–117 ± 114[c]
Papa Uvas	FIV	4475 ± 49	3357–2945 cal BC	5306–4894	–103 ± 80[c]
La Viña	Silo 16	4428 ± 83	3345–2911 cal BC	5294–4860	+200 ± 66[d]
Papa Uvas	F12	4421 ± 94	3355–2898 cal BC	5304–4847	+98 ± 106[d]
Papa Uvas	B10	4054 ± 195	3308–2027 cal BC	5257–3976	+327 ± 233[d]
Niebla	UE69	2067 ± 65	351 cal BC–71 cal AD	2300–1880	–163 ± 105[c]
El Eucaliptal	UE 4	1751 ± 84	73–530 cal AD	1877–1421	–142 ± 73[c]
Niebla	UE16	904 ± 40	1033–1213 cal AD	917–737	–82 ± 77[c]
Niebla	SA	218 ± 43	1524–1955 cal AD	427–0	–88 ± 54[c]
Weighted mean calculation ([c] negative ΔR values) 0.75; ($\chi^2_{:0.05}$ = 11.07)					
Weighted mean: **–108 ± 31 ^{14}C yr**					
Weighted mean calculation ([d] positive ΔR values) 1.09; ($\chi^2_{:0.05}$ = 5.99)					
Weighted mean: **+180 ± 66 ^{14}C yr**					

[1]Soares and Martins (2009, 2010).

Fifteen ΔR values were determined for the Barlavento coast, but 3 (+527 ± 54, +553 ± 86, and +380 ± 75 ^{14}C yr) were rejected in the calculation of the ΔR weighted mean value due to their χ^2 results (127.25; ($\chi^2_{:0.05}$ = 23.68)). With the remaining 12 values, a ΔR weighted mean value of +69 ± 17 ^{14}C yr was determined for this coastal region. For the Sotavento region, 13 ΔR values were obtained but 1 (+190 ± 51 ^{14}C yr) was rejected; the remaining 12 values were statistically indistinguishable (17.75; ($\chi^2_{:0.05}$=19.68)). A ΔR weighted mean value of –26 ± 14 ^{14}C yr was thereby obtained for the Sotavento coastal region.

For the Andalusian coast, 2 ΔR weighted mean values were obtained. Two sets of ΔR values were considered in the calculation of the weighted mean value, namely the 3 positive values (+200 ± 66, +98 ± 106, and +327 ± 233 ^{14}C yr) resulting in a ΔR weighted mean value of +180 ± 66 ^{14}C yr, and the remaining 6 negative values with a ΔR weighted mean value of –108 ± 31^{14}C yr. It must be noted that the ΔR weighted mean values obtained in previous research (Soares and Martins 2009, 2010) for the Barlavento coast (ΔR = +65 ± 20 ^{14}C yr) and the Andalusian coast (ΔR = –135 ± 20 ^{14}C yr) are not significantly different from the values determined in this study. The pairs of samples used in both studies for calculation of the ΔR weighted mean values (Barlavento and Andalusian coasts) are the same, with the observed small differences ascribed to the use of different calculation methods.

If the ΔR data given in Table 4 are plotted against time (Figure 2), the variability of the ΔR can be observed and compared among the 3 coastal regions. The positive ΔR values can be correlated with the presence of upwelling, while low or negative ΔR values correspond to weak, or even nonexistent, upwelling.

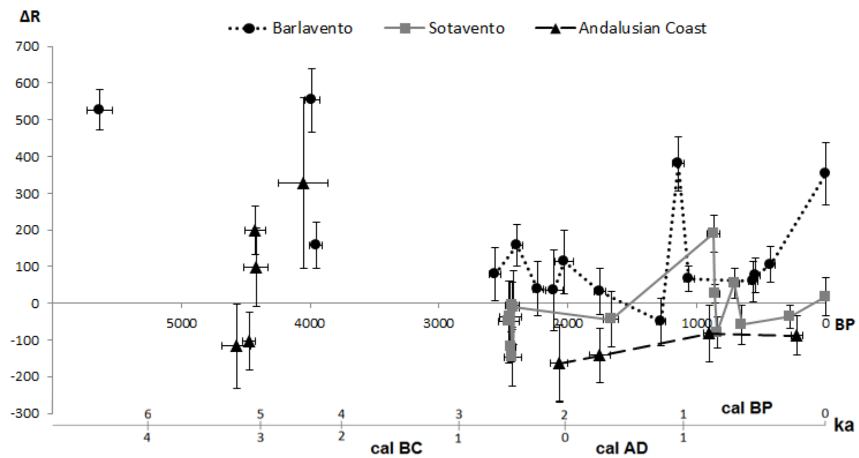

Figure 2 Marine ^{14}C reservoir effect for the 3 coastal regions. ΔR (±1σ) values are plotted versus terrestrial ^{14}C ages (±1σ).

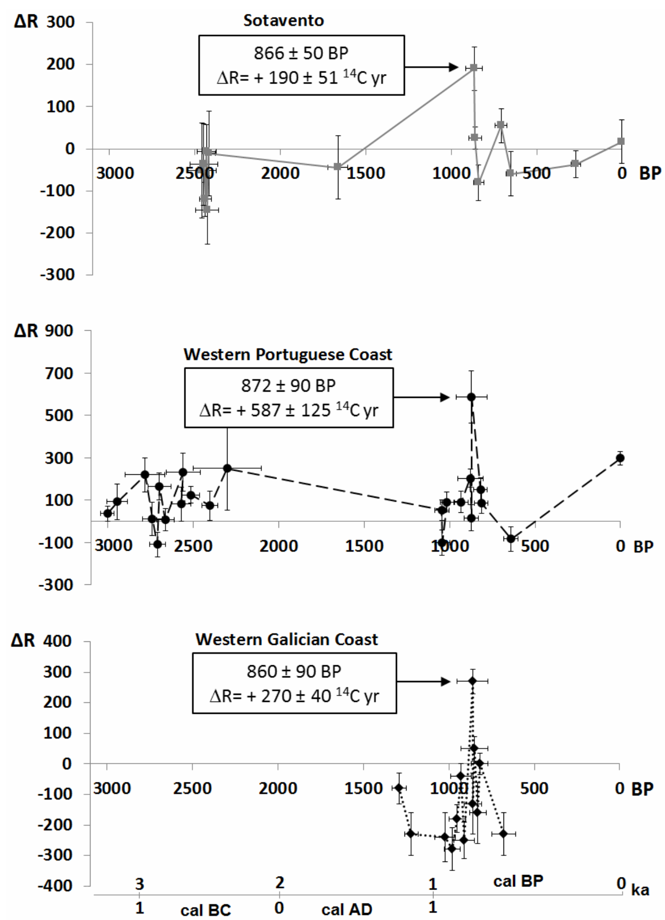

Figure 3 The synchronous peaks around 870 BP

The Barlavento coast has the higher ΔR values, the Andalusian coast the more negative ones, and the Sotavento coast has values between these two. As mentioned above, the Sotavento coast can be considered a transition zone between an area (the Barlavento coast) highly influenced by prolongation of the western coastal upwelling system into the southern Portuguese coast and an area where the upwelling regime is absent (the Andalusian coast). The ΔR values that determined for the 3 regions are in accordance with the prevailing oceanographic conditions. However, it must be noted that before 3 ka BP, positive ΔR values were determined for the Andalusian coast and highly positive values for the Barlavento coast, strongly suggesting a major change in the oceanographic conditions prevailing in the entire region of the southern Iberian Atlantic coast (see rejected values in calculation of ΔR weighted mean for the Barlavento region), as already seen in previous research (Soares and Dias 2006b; Soares and Martins 2010). A similar situation has been verified in 2 periods between the Last Glacial Maximum and the Holocene, which can be explained by the extension of the Azores Front eastward along the Azores Current into the Gulf of Cadiz (Rogerson et al. 2004). If we take into account that a strong upwelling is always associated with the Azores Front, the positive ΔR values that were determined for the time period in question can be easily explained.

Moreover, at 866 ± 50 BP, a peak (ΔR = +190 ± 51 ^{14}C yr) in the ΔR data set from the Sotavento coast was obtained, which matches another peak (ΔR = +587 ± 125 ^{14}C yr) obtained at 872 ± 90 BP in the western Portuguese coast (Soares and Dias 2006a) and another (ΔR = +270 ± 40 ^{14}C yr) obtained at 860 ± 90 BP in the western Galician coast (Soares and Dias 2007). These synchronous peaks (see Figure 3) can be related with the cold event at 0.8 ka cal BP (deMenocal et al. 2000), which in turn can be related with the climatic reorganization associated with the end of the Medieval Warm Period and the beginning of the Little Ice Age.

CONCLUSIONS

A record of past reservoir ages is preserved in the contemporary marine and terrestrial material, which can provide valuable information on the intensity of coastal upwelling and paleoenvironmental processes in marine regions influenced by this phenomenon. We built on the previous research of ΔR in the southern Atlantic Iberian coast, adding new ΔR values for the Sotavento coastal region, an area not yet analyzed. At the same time, using a new calculation approach, ΔR weighted mean values were recalculated for the Barlavento and Andalusian coasts. The results for the last 3000 yr (ΔR = +69 ± 17 ^{14}C yr, Barlavento coast; ΔR = –26 ± 14 ^{14}C yr, Sotavento coast; ΔR = –108 ± 31 ^{14}C yr, Andalusian coast) are in accordance with the oceanographic conditions present in each area.

On the other hand, a peak in the ΔR data set for the Sotavento coast was identified at 866 ± 50 BP, which can be related to the Bond event of 0.8 ka cal BP. Finally, the obtained data suggests that very different oceanographic conditions (high positive ΔR values) prevail in the Barlavento and Andalusian coastal areas and, consequently, in all the northern Gulf of Cadiz region during the 5th millennium cal BP, perhaps due to the extension of the Azores Front eastward along the Azores Current penetrating into the Gulf of Cadiz.

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